INTEGRATION OF RISK AND MULTIPLE OBJECTIVES IN PRIORITY SETTING FOR AGRICULTURAL RESEARCH

- The Case of the National Dairy Research Program in Kenya -

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Präsident
der Humboldt-Universität zu Berlin
Prof. Dr. Dr. h. c. Hans Meyer

Dekan der
Landwirtschaftlich-Gärtnerischen Fakultät
Prof. Dr. Dr. h. c. Ernst Lindemann

Gutachter: 1. Prof. Dr. Dieter Kirschke
2. Dr. habil. Christian Franke
3. Prof. Dr. Hassan Pirasteh

Tag der mündlichen Prüfung: ....

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLES AND FIGURES IN THE APPENDICES

TABLES:

FIGURES:

LIST OF ACRONYMS AND ABBREVIATIONS

INSTITUTIONS AND ORGANISATIONS:

CGIAR	Consultative Group for International Agricultural Research
FAO	Food and Agriculture Organisation of the United Nations
HUB	Humboldt-Universität zu Berlin
ICRISAT	International Crop Research Institute for the Semi-Arid Tropics
ILRI	International Livestock Research Institute
IMF	International Monetary Fund
ISNAR	International Service for National Agricultural Research
KARI	Kenya Agricultural Research Institute
KCC	Kenya Creamery Co-operative
NAHRC	National Animal Husbandry Research Centre
NARP	National Agricultural Research Plan
NARS	National Agricultural Research System
NDCRP	National Dairy Cattle Research Program
NDDP	National Dairy Development Project
NRC	National Research Centre
RRC	Regional Research Centre
TAC	Technical Advisory Committee
UNEP	United Nations Environmental Program
UNIDO	United Nations Industrial Development Organisation

TECHNICAL EXPRESSIONS:

AEZ	Agro-ecological zone
AH	Animal health
AHP	Analytic Hierarchy Process
AI	Artificial insemination
AR	Adoption rate
B-RAC	Break-even risk aversion coefficient
BR	Breeding and genetic improvement
CARA	Constant absolute risk aversion
CBR	Cost-benefit ratio
CDF	Cumulative distribution function
CEI	Certainty-equivalent index
CRRA	Constant relative risk aversion

CS	Consumer surplus
CV	Coefficient of variation
DARA	Decreasing absolute risk aversion
DRRA	Decreasing relative risk aversion
DEMP	Direct expected maximising non-linear programming
DSS	Decision support system
ECF	East coast fever
EDF	Empirical distribution function
EMV	Expected monetary value
EP	Expo power function
EU	Expected utility
EV	Expected value-variance
EVIU	Expected value of including uncertainty
FR	Feed resources and utilisation
FSD	First-order stochastic dominance
GIS	Geographic information system
GS	Government surplus
GSD	Generalised stochastic dominance
GSDP	Generalised Stochastic Dominance Program
HR	High rainfall
IARA	Increasing absolute risk aversion
IRRA	Increasing relative risk aversion
KSh	Kenya Shilling
LHS	Latin hypercube sampling
LP	Linear programming
LR	Low rainfall
MAUT	Multi-attribute utility theory
MOP	Multi-objective programming
MOTAD	Maximisation of total absolute deviation
MP	Mathematical programming
MR	Medium rainfall
NPV	Net present value
PDF	Probability density function
PS	Producer surplus
PV	Present value

q-FSD	Quasi-first-order (first-degree) stochastic dominance
q-SSD	Quasi-second-order (second-degree) stochastic dominance
QRP	Quadratic risk programming
R&D	Research and Development
RS	Research success
SD	Stochastic dominance
SDWRF	Stochastic dominance with respect to a function
SE	Socio-economics
SSD	Second-order stochastic dominance
TIES	Technology Impact Evaluation Simulator
TS	Total surplus
TSCU	Two-stage constraint utility
TSD	Third-order stochastic dominance
TSEU	Two-stage expected utility
UEP	Utility efficient programming
VBA	Visual Basic for Applications
YI	Yield increase

GERMAN ABBREVIATIONS

sog.	sogenannte
z.B.	zum Beispiel

ZUSAMMENFASSUNG

Das System der öffentlich finanzierten Agrarforschung in Entwicklungsländern steht vor großen Veränderungen. Die finanziellen Zuwendungen aus den öffentlichen Haushalten nationaler Regierungen und internationaler Entwicklungsorganisationen sind nicht mehr durch stetiges Wachstum gekennzeichnet sondern stagnieren. In Einzelfällen sind sogar drastische Rückgänge des Budgets für Agrarforschung zu beobachten (z.B. internationale Forschungszentren der CGIAR Gruppe). Demgegenüber steht die Notwendigkeit, mit neuen, aufwendigen und teuren Forschungsvorhaben, z.B. in den Bereichen Ressourcenschutz, Biotechnologie oder Gendatenbanken, der wachsenden entwicklungspolitischen Anforderung zur Ernährungssicherung, Armutsbekämpfung und Nachhaltigkeit gerecht zu werden. Diese Entwicklungen haben in den letzten Jahren einen starken Anpassungsdruck ausgelöst, und Agrarforschungsinstitutionen zu vermehrten Anstrengungen in der langfristigen Planung und dem selektiven Einsatz der zur Verfügung stehenden Forschungsmittel gezwungen. Die in diesem Zusammenhang zu treffenden Planungs- und Entscheidungsaufgaben, die unter dem Begriff der Prioritätensetzung zusammengefaßt werden können, sind vielschichtig und umfassen die Allokation von Forschungsressources auf verschiedene Länder und Regionen, unterschiedliche Forschungsprogramme, Produktgruppen und Institutionen.

Spezielle Planungsverfahren sind zur Prioritätenbestimmung im Einsatz, in deren Mittelpunkt die Wirkungsanalyse, d.h., die explizite Bewertung und den Vergleich der voraussichtlichen Wirkungen von Forschungsvorhaben, steht und ein entscheidendes Kriterium für die Auswahl von Forschungsvorhaben sowie der resultierenden Allokation von Forschungsmitteln darstellt.

Die Planungs- und Entscheidungsaufgabe in der Prioritätensetzung im Agrarforschungsbereich fällt in die Kategorie der komplexen Probleme. Die Komplexität des Planungsgegenstands Agrarforschung ist bedingt durch die den öffentlichen Forschungsinstitutionen auferlegten multiplen sozialen und ökonomischen Zielvorgaben, die einerseits eine Ausweitung der Wirkungsanalyse hinsichtlich der Vielfalt der Ziele notwendig machen, und andererseits konkrete Entscheidungen zur Gestaltung von durchführbaren Forschungsprogrammen und Projekten erschweren. Hinzu kommt, daß Forschungsplanung in einem durch erhebliche Unsicherheit und Unvorhersehbarkeit geprägten Umfeld stattfindet. Die Instabilität landwirtschaftlicher Märkte, witterungsbedingte Ertragsschwankungen, sowie interne Ursachen, z.B. der lange Planungszeitraum von Forschung, die Unsicherheit in der Entwicklung, Verbreitung und

Adoption von neuen Technologien, verleihen den Planungsannahmen und den darauf aufbauenden Bewertungsergebnissen einen starken subjektiven und spekulativen Charakter.

Zahlreiche Beispiele aus der Literatur belegen, daß das Problem der Komplexität und Unsicherheit in der Prioritätensetzung zwar thematisiert worden ist, aber die angewandten Planungsmethoden entweder gar nicht oder nur unzureichend diese Probleme behandelt haben, wie Beispiele aus "Scoringverfahren" deutlich belegen.

Diese Studie greift diese methodischen Defizite erneut auf, und behandelt konkret die Fragestellung, mit welchen alternativen Methoden und Modellen aus der Ökonomie der Umgang mit Komplexität und Unsicherheit in der Prioritätensetzung systematisiert und verbessert werden kann. Ziel ist es nicht ein neues Verfahren zu entwickeln, sondern bestehende Ansätze mit formalen Bewertungs- und Entscheidungsmethoden zu ergänzen. Eine grundlegende Prämisse der erweiterten Ansätze ist die Kompatibilität mit dem vorgegebenen restriktiven Planungsrahmen in der Prioritätensetzung, die ein hohes Maß an Praktikabilität, methodischer Klarheit und Verständlichkeit sowie geringe Datenerfordernis voraussetzt.

Die in dieser Arbeit dargestellten Methoden werden an einem konkreten Beispiel aufgezeigt. Als Fallstudie dient ein im Jahr 1996 durchgeführter Workshop zur Prioritätensetzung für das nationale Michviehforschungsprogramm in Kenia. Die konkrete Aufgabe des Workshops war die Bewertung und Prioritätensetzung für eine Gruppe von 19 geplanten Forschungsprojekten zur Entwicklung von neuen Technologien in der kenianischen intensiven Milchviehhaltung.

Eine wesentliche Grundlage für die in dieser Arbeit angewandten Methoden bildet zunächst die Entwicklung eines stochastischen Bewertungssystems für die Investitionsanalyse der geplanten Forschungsprojekte. Die numerische Simulation (Monte Carlo Simulation) dient dabei der Reproduktion von stochastischen Modellvariablen und Parametern. Aus den vorliegenden Befragungsergebnissen der kenianischen Experten zu den voraussichtlichen Wirkungen der geplanten Forschungsprojekte lagen Wahrscheinlichkeitsverteilungen bezüglich der erwarteten Ertragssteigerung vor, die als stochastische Variablen in die Investitionsanalyse integriert wurden. Das Ergebnis dieser stochastischen Bewertung sind Wahrscheinlichkeitsfunktionen (Risikoprofile) für den Gegenwartswert sowie die Kosten-Nutzenrelation als wesentliche Bestimmungsfaktoren für die Wirtschaftlichkeit der untersuchten Forschungsprojekte. Die stochastische Dominanzanalyse dient in einem weiteren Schritt zum Vergleich der Forschungsprojekte und, differenziert nach Risikopräferenzen, zur hierarchischen Einordnung in eine Rangliste als Indikator für die Priorität eines Forschungsprojektes.

Zur konkreten Abbildung von Komplexität in der Planung von Agrarforschung werden verschiedene mathematische Programmierungsansätze eingesetzt. Die Intention der mathematischen Programmierung im Kontext von Prioritätensetzung innerhalb eines Forschungsprogrammes ist die Nutzung als Planungsinstrument zur Auswahl von alternativen Forschungsaktivitäten (Projekte) unter Berüchsichtigung von Ressourcenverfügbarkeit, diversen Entscheidungsrestriktionen und multiplen Forschungszielen. Dabei soll untersucht werden, wie diese Faktoren auf die Richtung und Zusammensetzung eines Forschungsprogrammes einwirken. Ein inhaltlicher Schwerpunkt bildet dabei die "trade-off" Analyse zwischen konfligierenden Forschungszielen.

Im wesentlichen werden drei unterschiedliche mathematische Programmierungsansätze entwickelt und angewandt. Ein deterministisches Basismodell bildet den Einstieg in die Analyse von multiplen Zielen sowie die Einbeziehung von unterschiedlichen Budgetierungsoptionen, dem Risiko von Forschungsmißerfolgen und Projektinteraktionen. Stochastische Risikoprogrammierungsmodelle erweitern die Analyse hinsichtlich der Einbeziehung von stochastischen Variablen und Risikopräferenzen der Entscheidungsträger. Ein dritter Modellansatz behandelt die simultane Darstellung von Risiko und multiplen Zielen.

Die Ergebnisse der stochastischen Dominanzanalyse in dieser Fallstudie unterstreichen die Tatsache, wie wichtig die Berücksichtigung von Unsicherheit für eine qualifizierte Forschungsplanung ist. Der direkte Vergleich der Forschungsprojekte anhand der Risikoprofile zeigt auf, daß in vielen Fällen die Vorteilhaftigkeit eines Forschungsprojektes nicht eindeutig festgestellt werden kann, sondern abhängig ist von der unterstellten Risikoeinstellung des Betrachters. Dies kommt deutlich durch den starken Einfluß von Risikopräferenzen auf die Rangliste der Projekte zum Ausdruck, und betrifft im besonderen Maße Projekte mit dem größten wirtschaftlichen Potential im oberen Rangbereich. Konkret bedeutet dies, daß ein überwiegend auf Sicherheit bedachtes Forschungsmanagement eine andere Projektauswahl und auch Reihenfolge in der Implementierung treffen würde als bei einer weniger risikoscheuen Einstellung.

Aus der Sicht eines Planers ist die Erkenntnis wichtig, daß im konkreten Beispiel eine differenzierte und vorsichtige Interpretation und Beratung des Forschungsmanagements vorzunehmen ist. Dies steht im Gegensatz zu einer deterministischen Investitionsanalyse, deren Eindeutigkeit der Bewertungsergebnisse zu irreführenden Schlußfolgerungen führen würde. Im Detail ist auf die seitens der Experten zu beobachtende Unsicherheit der Prognose der wirtschaftlichen Auswirkungen, und auch auf die Risikoeinstellung der Entscheidungsträger hinzuweisen. Ein weiterer Unsicherheitsfaktor stellt die Robustheit der

Ergebnisse aus der stochastischen Dominanzanalyse dar. Anhand der Bestimmung von Konfidenzintervallen für die Ergebnisse der stochastischen Dominanzanalyse mit Hilfe von "Bootstrapping" läßt sich dokumentieren, daß die Gefahr der Konstatierung falscher Dominanzbeziehungen zwischen einzelnen Forschungsprojekten nicht unerheblich ist.

Als Einstieg in die Modellierung von Komplexität wurde die Basisversion eines mathematischen Programmierungsmodells zur Analyse von Verteilungseffekten und die Einbeziehung von unterschiedlichen Budgetierungsstrategien eingesetzt. Da der wirtschaftliche Nutzen der Forschungsprojekte hauptsächlich in den produktiven Regionen in Kenia realisiert würde, sind drei verschiedene Entscheidungsszenarien abgebildet, die eine Umverteilung des Forschungsnutzens zugunsten der marginalen Produktionsstandorte und urbanen Zentren intendieren. Die gemeinsame Erkenntnis aus den Modellergebnissen der drei Szenerien ist, daß die Opportunitätskosten der stärkeren Berücksichtigung von Verteilungsgerechtigkeit, ausgedrückt als Verlust an wirtschaftlichen Nutzen, erheblich sind. Ähnliche Schlußfolgerungen können im Hinblick auf unterschiedliche Budgetierungsoptionen, z.B. die Festlegung von Budgetunter- und Obergrenzen für Projektgruppen mit ähnlichen Forschungsthemen, gezogen werden.

Im Vergleich zu der Verteilungsproblematik wirkt sich Risikoverhalten weniger pointiert auf planerische Entscheidungen aus. Quadratische Programmierungs- und Nutzenmaximierungsmodelle liefern als Ergebnis eine Vielzahl von alternativen Forschungsportfolios, die eine andere Zusammensetzung aufweisen als Portfolios unter deterministischen oder risikoneutralen Bedingungen. Dennoch sind die Unterschiede bezüglich der Wirtschaftlichkeit nicht groß. Für die konkrete Fallstudie bedeutet dies mit anderen Worten, daß der monetäre Gewinn einer Portfolioanalyse unter Unsicherheit hinsichtlich verbesserten Planungsentscheidungen eher marginal ist. Als Erkenntnis ist weiterhin anzumerken, daß beide Modellansätze unterschiedliche Ergebnisse liefern. Im Hinblick auf die Qualität der Ergebnisse, also die Generierung von effizienten bzw. pareto-optimalen Lösungen, sind Nutzenmaximierungsmodelle eindeutig vorzuziehen.

Als zentrale Fragestellung bei der simultanen Betrachtung von Risiko und multiplen Zielen steht die Diskrepanz zwischen verteilungsorientierter und effizienzorientierter Forschungsplanung. Dabei werden Verteilungsaspekte unter zwei unterschiedlichen Gesichtspunkten definiert. Zum einem wird eine Differenzierung der Allokation des Forschungsnutzens nach regionalen Gesichtspunkten vorgenommen durch eine Gruppierung der Regionen in sog. "Haupt-" und "marginale" Standorte, und zum anderen erfolgt eine Aufteilung nach gesellschaftlichen Gruppen in Produzenten und Konsumenten. Aus den Modellergebnissen wird deutlich, daß unter den gegebenen Planungsoptionen eine spezielle

Förderung von Produzenten- sowie Konsumenteninteressen nur beschränkt möglich ist, und die jeweiligen Optionen nur geringe Verteilungswirkungen erzielen. Diese Feststellung ist prinzipiell gültig, sowohl unter risikoaversen als auch unter risikofreudigen Entscheidungsprämissen. Ganz anders stellt sich die Situation innerhalb der regionalen Gruppen dar. Dort würden je nach Gewichtung der regionalen Gruppen starke Umverteilungeffekte in den regionalen Einkommen auftreten. Im Vergleich zu einer "neutralen" Ausrichtung der Forschung wäre eine prioritäre Ausrichtung auf eine der beiden Gruppen mit großen Effizienzverlusten verbunden.

Zur abschließenden Bewertung der in dieser Arbeit vorgestellten quantitativen Planungs- und Bewertungsansätze sind folgende Anmerkungen wesentlich. Numerische Simulation, stochastische Dominanz und mathematische Programmierung vereint als integrierter Ansatz in der Prioritätensetzung für Agrarforschung deckt ein weites Spektrum an ökonomischer Analyse ab. Die Formalisierung von komplexen Entscheidungssituationen sowie die Quantifizierung von Forschungsrisiko und Unsicherheit in den Planungsannahmen stellen eine wesentliche Verbesserung der planerischen Qualitäten von Prioritätensetzung dadurch dar, daß die Wirkung von Forschung wesentlich detaillierter dargestellt wird, die für das jeweilige Forschungsinstitut spezifischen Rahmenbedingungen eine stärkere Berücksichtigung finden, und zahlreiche alternativen Handlungsoptionen aufgezeigt werden können. Die Anwendbarkeit dieser Methoden ist nicht limitiert auf diese Fallstudie, sondern ist generell auf viele ähnlich konzipierte Prioritätensetzungsbeispiele im Bereich der produktspezifischen Agrarforschung übertragbar. Die Kosten allerdings sind die Einarbeitung in die modelltheoretischen Grundlagen, ein mehr an Modellierungsaufwand und die Verarbeitung und Präsentation von zusätzlichen Datenmengen und Informationen.

SUMMARY

Public agricultural research systems in developing countries have entered an era of resource scarcity. Funds from national governments and the international donor community do not increase as much as in the past decades. There are many examples where research funding has been significantly reduced, e.g., in the international research centres of the CGIAR group. At the same time agricultural research must continue with its efforts to contribute to food security, poverty alleviation and sustainable production systems by investing in new and expensive research areas such as biotechnology, resource conservation and the like. These developments have put agricultural research systems under increasing pressure to undertake long-term planning and make a more selective use of their available resources. Priority setting has become a key word to research management which subsumes a diverse set of planning and decision making tasks. Priorities must be set for the allocation of research resources to different countries, regions, research programs, commodities and factors, as well as for different research institutions.

A variety of formal priority setting methods exist in practical applications. The fundamental part of making decisions on the allocation of resources is the assessment and comparison of the likely impact of research activities on pursued research objectives. Planning and decision making in priority setting of agricultural research can be characterised as a complex task. The complexity is due to the broad mandate of agricultural research in agricultural development including a variety of social and economic objectives. Yet such enormous responsibilities do not only make the assessment of the impact of research an onerous task but also complicates decision making on the type of research to fund and the future directions of a research program. Further complexity is added through uncertainty which is notorious in the planning environment of agricultural research. Unstable agricultural markets, exposure of production to climatic hazards and several internal sources of uncertainty in the research system, such as long planning horizon, the risks in the development, dissemination and adoption of new technologies, make research planning a highly conjectural and uncertain venture.

Examples from the literature show some evidence for the recognition of decision complexity and uncertainty in priority setting but methodological approaches to these problems are yet not satisfactory. The aim of this study is to apply formal economic methods for an improved treatment of decision complexity and uncertainty in Priority setting. These methods are illustrated by using a priority setting example from Kenya. In 1996, the Kenyan Agricultural Research Institute (KARI) conducted a priority setting exercise for its national dairy

research program where a set of 19 proposed dairy research projects had to be evaluated and prioritised.

A prerequisite for the application of the economic methods is the development of a stochastic evaluation system. In a preliminary step the deterministic economic surplus framework within which the welfare effects of the 19 dairy research activities are calculated across different regions in Kenya is transformed into a stochastic system. Numerical simulation is used to reproduce stochastic input variables. For the dairy case study this is done by explicit incorporation and reproduction of the probability distributions of the research projects' yield increase parameters. Evaluation outcomes are probability distributions (risk profiles) of the net present value and cost-benefit ratios as the two major economic indicators for the research projects. In a next step stochastic dominance analysis is employed as a decision rule for uncertain prospects to compare and rank the set of research alternatives based on their stochastic returns to research.

The method used in this study to incorporate complexity in research planning is mathematical programming. In the context of priority setting for agricultural research, the main idea behind mathematical programming is the optimal selection of a set of research activities given limited resource availability, decision constraints and the pursuit of multiple objectives. Special interests is placed on how changes in one or several decision factors affect the direction and the composition of a research program. Basically the study develops and applies tree different mathematical programming approaches. A deterministic baseline model starts with the analysis of multiple objectives and integrates a variety of budgeting strategies, constraints on research success, and project interactions. Risk programming models incorporate further the uncertainty surrounding impact estimates of research and risk preferences of decision makers. A final model specification addresses the simultaneous analysis of risk and multiple objectives.

Results from the case study show that comparing and ranking research projects by stochastic dominance criteria yield a different picture compared to a deterministic analysis. For many projects is impossible to make clear statements about their superiority or inferiority over other projects without explicit incorporation of the attitudes towards risk. This becomes obvious from the large variability in the project ranks that are examined across a broad range of different risk preferences. This implies in other words, that risk averse decision making would opt for a rather different set of projects than those willing to take higher risks. Analysts who have to translate these findings into decision advise would have to point at the high uncertainty surrounding the evaluation results, the ambiguity of making clear statements about project ranks and the importance that must be given to the attitudes towards risk.

Another element of uncertainty surrounds the stochastic dominance results. The robustness of the results as indicated by the size of the confidence intervals may not always be sufficiently robust as to ascertain correct dominance relationships for every pairwise comparison of the research projects.

The specific intention of the baseline mathematical programming model was to analyse the distributional consequences and different budgeting strategies on the resultant research plans. Given the fairly unbalanced regional distribution of the economic gains from dairy research three different scenarios have been examined that are aimed at securing higher shares in the economic gains for the disadvantaged marginal regions and the urban centres in Kenya. A common finding is that any adjustments towards a more balanced distribution would result in high opportunity costs in terms of foregone overall economic gains to the country. Similar finding hold true for several different budget strategies compared to a free allocation of research funds for the dairy program.

Less pronounced are the effects of different risk attitudes. Although quadratic risk programming and utility efficient programming models come up with several alternative research portfolios that differ markedly from research portfolios in a deterministic analysis or assuming risk neutrality, but the economic implications are not strong. Thus, one can conclude that under the particular conditions of this case study the extra effort of a portfolio analysis under risk and the elicitation of decision makers' risk preferences do not pay-off much. Another interesting finding is that the two risk programming models yield rather different results, whereas the accuracy of the results (in terns of efficient and pareto-optimal solutions) is always met with utility efficient programming model but not with quadratic risk programming model.

The central point of interest in the multi-objective risk programming model is the examination of the trade-offs between efficiency and equity. Equity concern is looked at from two different angles. First, equity is conceptualised in terms of the spatial distribution of research benefits across different regions by subdivision of the dairy regions into a "core" dairy and a "marginal" dairy group. The second concept for equity is by consumers and producers of milk as beneficiaries of the gains from research. Model results reveal the limited scope of directing research plans generated from the 19 projects either for the sake of consumers or producers. Though different plans can be proposed, the economic implications for consumers and producers are rather modest which is true regardless the assumed attitudes towards risk. The picture looks rather different if plans are made with changing emphasis placed on the importance of different dairy groups. If plans would prioritise either the "core" or the "marginal" dairy group, this would lead to enormous losses in overall economic gains.

For a final assessment of the methods introduced in this study the following remarks are worth mentioning. Numerical simulation, stochastic dominance and mathematical programming applied as an integrated approach to the analysis of research investments and as decision aid in priority setting covers a wide spectrum of economic analyses. The formal incorporation of decision complexity and quantification of research risks enable analysts and advisors of research managers to undergo a much more careful inspection of the ex-ante effects of research which finally materialise in better informed and differentiated advise to research planners, thereby indicating the potentials but also the limitations of their work. These methods are not specific to the case study but are applicable to many similar priority setting exercises for commodity research programs. The costs of these enhanced methods are advanced skills in economic modelling, some additional time in model set-up and model run, data processing and synthesis of model results to arrive at practical recommendations.

1 Introduction

1.1 Agricultural Research and the Need for Priority Setting

Agricultural research is widely recognised as a key factor in expanding agricultural production in developing countries in order to match the increasing demand for food, to alleviate the problem of malnutrition of around 1 billion people, and to generate income in rural areas. The land frontier, where new land can be brought under cultivation are about to be depleted, thus, the challenge to overcome the global food problems can only be met by means of technical innovations in production, processing and marketing of agricultural products (SCHUH 1987, p. 72). The development and promotion of new and improved technologies in these areas through publicly financed research and extension systems have been central topics in agricultural development. Public investments in agricultural research have shown high economic returns which were considerably higher than returns from many other public investments elsewhere.[1] Assuming that the rates of return to research reported in the literature are reasonably accurate, this implies that the amount invested in research has been suboptimal supporting the hypothesis of underinvestment in agricultural research. The explanation for such an underinvestment varies with different authors.[2]

Public agricultural research has entered an era of resource scarcity and there is little hope that, despite the high returns, investment in research will increase significantly. The funding of research in national agricultural research institutions (NARS) in developing countries has become tighter and some evidence of donor fatigue in international organisations is already apparent (ALSTON et al. 1997, p. 1). Unfortunately, governments in developing countries are unable (or unwilling) to increase public spending in order to compensate for the inadequate involvement of the international donor community.[3]

In recent years the donor community has started to make financial support increasingly dependent on improved efficiency pinpointing at several structural deficits that have emerged over the last few decades. Public agricultural research systems have expanded considerably through creation of new research programs and more employment of the agricultural scientists without proportionately increasing overall public spending. This has created a quite untenable situation. Research budgets over the last two decades have shown

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[1] An overview of the economic returns from investments in agricultural research is presented e.g., in PINSTRUP-ANDERSON (1982, p.100 ff); ECHEVERRIA, 1990, p. 3).

[2] See, among other studies, HERFORD and SCHMITZ (1977); EVENSON et al. (1979); OEHMKE (1986).

[3] Many developing countries are currently participating in structural adjustment programs of the International Monetary Fund (IMF) and Worldbank whose macroeconomic policy reforms may have a negative impact on public research institutions. For example, TABOR (1995, p. 37-38) reports that research institutions in several African countries are faced with inadequate and unstable financing during adjustment.

a steady reduction in the budget per researcher and research project (see CRAIG et al. 1991, p. 132 ff.), thus posing a serious threat to the quality of public agricultural research. Therefore, NARS are coming under increasing pressure to improve efficiency by better management practises aimed at increasing internal transparency, reducing redundancy in research activities, and promoting long-term planning.

To make agricultural research institutions more efficient, priority setting has established itself as an important tool in research management for improving strategic planning and arriving at a more efficient allocation of scarce research resources. The limitation of funds has set the stage for redefining priority setting in agricultural research. Whereas priority setting had previously meant adding new programs to the annual "wish list", the present day definition is more painful and involves constant or decreasing budget and the reallocation of research resources by evaluating and ranking research activities, eliminating some and adding others.

1.2 Achievements and Shortcomings of Priority Setting Methods

Substantial efforts have been made in recent years to improve the tools of priority setting. Starting as a rather unstructured and informal decision making process priority setting has now developed into a formal and almost standardised procedure that is applied world-wide. Formal approaches usually mentioned in the context of priority setting are the congruence and precedence methods, the least sophisticated and simplest approaches; multi-criteria scoring models, economic evaluation models such as cost-benefit analysis, and economic surplus approaches, the Analytic Hierarchy Process (AHP), mathematical programming and simulation models.[4]

Priority setting involves decisions to be made on several levels of a national research institution; on the institute level between alternative research programs, on the research program level between research alternatives of the same research program, and on the regional level between research activities, scientists and budgets to be allocated across regions. A key role of priority setting and the use of formal priority setting methods is the evaluation of research alternatives with respect to their potential impact on pursued research objectives. Such impact analyses of research alternatives are aimed at bringing more objectivity into the planning process while placing increasing emphasis on measurable and defensible decision criteria. The decisions at stake are essentially those of budgetary allocation. Almost all priority setting efforts in practise, and also the majority of formal methods, derive allocation decisions from a hierarchy of individual research alternatives

[4] An overview of priority setting and research evaluation methods is presented e.g., in CONTANT and BOTTOMLEY (1988); NORTON and DAVIS (1981); and ALSTON et al. (1995). The latter authors place a strong emphasis on economic surplus methods.

which is synthesised from research impact results. Research activities are defined in terms of discrete investment alternatives and decisions are made on the types and sequence of research investments to implement and fund. This study sees priority setting of agricultural research investments exactly under this premise.

A more demanding task is the question of optimal allocation of funds to different lines of research. Optimal resources allocation is a separate task for which the assessment of research priorities alone is not yet sufficient (except for the precedence and congruence rules). From an economic point of view the allocation is optimal if the marginal return on investment of all research options is equal. The determination of the marginal return on investment as a necessary prerequisite for optimising research resource allocations would require to establish some functional relationship between the level of research resources invested and the resulting research benefits which is extremely hard to estimate. For this reason the optimal allocation of research resources has not been a central focus in practical applications.

Agricultural and resource economists have in the past contributed much to the analysis of research investments. Priority setting has enormously benefited from this economic expertise and has helped to establish a sound methodological basis in economic evaluation techniques. Agricultural economists have developed economic models to measure the economic gains from research investments based on applied welfare analysis, starting from rather simple cost-benefit analysis and ending with complex multi-market and multi-period trade models. Resource economists have done much work on measurement concepts of the gains from research for so called "non-economic" objectives, such as the preservation of natural resources with respect to soil, water, or bio-diversity.

However, the majority of research investment studies reported in the literature do not sufficiently recognise that investing in research in a risky business and the results from an ex-ante evaluation of research are notoriously uncertain and unpredictable. Deterministic models continue to dominate research investment analysis although planners and decision makers are aware of the manifold sources of risk and uncertainty in their work.[5] This

[5] The terms "risk" and "uncertainty" are often used interchangeably. Likewise, the author treats uncertainty and risk more or less as synonyms. However, one common distinction between risk and uncertainty is that risk implies imperfect knowledge where the probabilities of the possible outcomes are known, and uncertainty exists where these probabilities are not known. To the author's opinion this distinction is not very helpful in the context of this work because cases where probabilities are objectively known are the exception rather than the rule in decision making. On the other hand, a problem characterised as uncertain would not be amenable to decision theory since nothing is known or assumed about the probability of occurrence. In this study "risk" is mainly used in the context of a decision making situation and decision makers' attitude towards risky situations while "uncertainty" characterises the stochastic nature of model variables.

evidence has led to the presumption that ignoring risk and uncertainty is a "chronic disease" of planners, not only in agricultural research. Some accountancy of risk and uncertainty is usually made by performing various sensitivity analysis on critical model parameters e.g., market prices, adoption rates of technology, research costs, etc. The use of sensitivity analysis is open to much criticism because of its simplistic treatment of risk, the incomplete information of uncertainty, and the limitations of sensitivity results for decision making.

Thinking about risk in agricultural research planning has become more important. Research experiments are far more resource demanding and costly than in the past. They often require highly sophisticated and costly technical equipment whose investments must be planned carefully on grounds of reliable cost-revenue calculations. Also new types of research are inherently more risky than traditional research, e.g., bio-technology and genetic research where high risks lie in the successful generation of a new technology or product. Furthermore, NARS increasingly rely on funds from foreign donors who make their future commitment dependent on a successful performance of a funded research activity.

A different line of arguments concerns the attitudes towards risk. Decision rationality prescribes that decisions are not invariant to the perception of risk. Risk averse decision makers behave and decide differently than risk prone decision makers. The appropriate criteria for risk neutrality is based on the expected value of the return to a research investment, while risk aversion implies that a risk component (e.g. the variance around the expected value) is traded off against (subtracted from) the expected value. The greater the discrepancy between the actual risk preferences of decision makers in agricultural research and assumed risk neutrality in deterministic investment analysis the more important becomes the formal recognition of the riskiness of a research investment. Unfortunately, little is known about risk preferences of public agricultural research institutions. Most risk studies have concentrated on farmers, especially small-scale framers in developing countries (e.g., BINSWANGER 1980). There are few arguments that can brought against risk neutrality of research institutions, e.g., careful use of funds from external sources advocate risk aversion, while the mandate to bring about technical progress and innovations would advocate risk prone behaviour.

In light of these arguments, economists involved in priority setting are well advised to turn a stronger focus on the incidence of risk and uncertainty and to complement investment analysis with some sort of formal, perhaps quantitative, risk analysis. This way, research management can be provided with important insights into the individual "risk profile" of a research investment, the different sources of risks and their relative importance, which are preliminary steps towards the development of a more comprehensive risk management system. Apart from assessing risk, economists can offer help in guiding research management through the process of decision making when research investments are represented as uncertain outcomes.

Cutting across the priority setting literature another deficiency becomes obvious. Economists and analysts involved in priority setting have paid much attention to the research evaluation issue, but little attention to how evaluation results are turned into future research plans and the allocation of resources. Priority setting has, by its nature, a strong decision-oriented focus. Unlike in other fields of planning, e.g., farm business and private companies, where similar types of investment decisions are involved and often studied through formal planning and decision methods, research investment decisions continue to evolve through informal discussion and consultation of the research management.

The decision problems however, that must be solved in priority setting are usually very complex. The complexity of research decisions is mainly attributable to the fact that public agricultural research takes place in a multiple-objectives environment. Unlike private research, public research has a much broader research agenda under which they must operate and contribute to agricultural development. Two decades ago, agricultural development and research were operating under the agenda of economic growth, and research was geared toward contributing to increased yield and reduction of the cost of production. Since then the interpretation of development and the agenda under which research must operate have become far more complex; including several new objectives such as equity, sustainability, food security and many more. In the future, priority setting efforts will inevitably have to deal with multiple research objectives since research planning and evaluation is expanding fast from commodity research into new research areas, e.g., factor research, sustainability research, or genetic resources where the effects of research need to be assessed on several non-efficiency objectives.

Undoubtedly, a multi-dimensional view of research is necessary, but this "objective-cocktail dilemma" does not only add additional work to the evaluation of research alternatives but also complicates the decision making process. Research objectives are often in conflict, e.g., research aimed at increased yield of a crop by higher doses of fertiliser and pesticides contradicts with the demand for sustainability production practises. To evaluate the effects of various research strategies on different objectives are complex to ponder. The same is true for decision makers who all have their different agenda and vested interests but must finally compromise and arrive at decisions for a research strategy. It is widely recognised that human beings are not especially good in handling such complex decision problems. As KIRSCHKE (1993, p. 3) remarks:

"*... people have difficulties to properly act in complex systems. Man is a typical trouble-shooter: When a problem comes up he immediately tries to solve this very problem without looking at the consequences of his action in a broader context ...*".

Solving complex decision problems such as those encountered in priority setting requires the use of mathematical models. Such models do not represent decisions as a whole, since many decision making aspects are intangible, but promote a systematic approach to the decision problem, increase the understanding of the complexity by breaking up the complexity into a hierarchical order and component parts.

So far, the most commonly used mathematical approaches to a multi-objective decision problem in priority setting have been scoring models. But they have been dealt with multiple objectives in a rather naive way. Shortcomings in the treatment of multiple objectives are mainly attributable to the widespread use of scoring models that are often applied in an ad-hoc fashion and whose decision-theoretic limitations are not fully recognised. This has led to poorly defined and overlapping research objectives, inaccurate identification of objective weights, and ignorance of functional relations between defined objectives or criteria (ALSTON et al. 1995, chapter 7). Scoring models have their strength in combining different benefit dimensions from different objectives but fall short in providing insights into the interaction of research objectives. When operating in a multi-objective planning environment analysts have an obligation to advise research managers as to the costs, in terms of opportunity forgone, of slanting research choices and plans in any particular direction. This is one reason, and a very compelling one, for advocating more advanced planning methods to the multi-objective decision problem. Especially methods from operations research and business management science, such as mathematical programming, deserve attention and it is worthwhile to study their potential for priority setting in agricultural research.

In the future, priority setting in agricultural research will be the rule rather than the exception. Along with this growing popularity, economists should contribute their part to provide practitioners and research management with procedures to organise and control the priority setting process, with applicable and easy-to-use evaluation and decision support tools, and with improved economic approaches to cope with peculiarities of agricultural research that makes the analysis and decision making of research investments an unique undertaking. This study tries to make such a contribution by applying some formal and quantitative economic modelling approaches to the field of risk and uncertainty, and multiple objectives where methodological deficiencies are still apparent.

1.3 Scope of the Study

The overall scope of the present study is to contribute to formal methods in priority setting for a more explicit representation of risk and uncertainty as well as of the inherent complexity of decision making in a multi-objective context. The objective is to provide some concepts, methods and criteria that can be used to advise research managers and decision makers in national agricultural research institutions who have to make strategic decisions in research program planning and to adjudicate on research resources allocations. The decision making and planning problem involves two tasks, the development of formal procedures and methods, and their actual application which is a precondition to assess the practical value of any methodological proposition.

The methods developed are applied to the conditions of a concrete priority setting exercise conducted and completed in 1996 for the national dairy research program of the Kenya Agricultural Research Institute (KARI). The priority setting case study provides a comprehensive documentation of the primary elicitation information collected from Kenyan dairy experts, the evaluation methodology for assessing gains from dairy research, and the final evaluation results. The case study constitutes a typical priority setting example for a research commodity program. The dairy research program has the mandate to pursue multiple research objectives, such as efficiency, equity, and sustainability, and the decision problem of the priority setting exercise is one of selecting research projects from a finite set of evaluated and prioritised projects that should be added to the current portfolio of the dairy research program. The case study provides an opportunity to exemplify the potential improvements of the enhanced methods with regard to its pursued objectives.

The means by which these methodological aspects in priority setting is addressed throughout this study is one of economic modelling. Traditionally, the limits to economic modelling were set by the availability of computer hardware and software technology. Much of this restriction has been removed and is not apparent any more. Moreover, there is a large variety of theoretical models for the treatment of risk and uncertainty, and the analysis of multiple objectives like probability theory and multi-objective decision theory.

The development and application of mathematical programming models as decision aid to cope with the complexity in decision making in priority setting constitute the central part of this study. Various types and degree of complexity are dealt with in different programming models and applied to deterministic, stochastic, single and multi-objective situations.

The contributions to improved incorporation and analysis of risk and uncertainty is accomplished through several tasks:

- the development of a stochastic evaluation framework where selected research parameters and the final returns to research are represented as stochastic variables;
- the quantitative evaluation of the individual riskiness of research projects;
- the application of formal decision criteria and methods for making choices under conditions of risk and deriving a rank order of rank of research projects;
- the incorporation of decision makers' preferences towards risk and the analysis of how changing risk preferences lead to alternative decisions and research plans.

Taking these tasks together, the study of risk and uncertainty rather concentrates on methodological aspects and on quantitative risk analysis applied to the conditions of research priority setting. Further steps need to be taken – but this is beyond the scope of this study – towards the development of a comprehensive risk management system as an integrated part in research planning.

Priority setting practitioners who might be inspired by some of methods and would like to integrate them into their own model are provided with programming source codes outlined in Appendices C of this study. Appendix C contains computer routines for numerical simulation, stochastic dominance analysis and other techniques: Routines are written in Visual Basic for Applications (VBA) and allow these techniques to be implemented on MS Excel spreadsheets.

1.4 Topical Outline

The study is organised around 8 chapters. Following chapter 1 as introduction to this work, Chapter 2 begins with an outline of the principal characteristics and definitions of priority setting in agricultural research, and the organisational framework within which individual working steps are defined and combined to a priority setting process. A next section addresses the choice of appropriate priority setting methods, including the amenability of different types and categories of research to formal evaluation and decision making approaches, and proposes criteria to assess the suitability of priority setting methods. Chapter 2 continues with a review of formal methods that are commonly used in priority setting for agricultural research and concludes with a critical assessment, the pros and cons of the different priority setting methods

Chapter 3 presents a review of the priority setting exercise for the national dairy research program of KARI conducted in 1996 which is used as a platform to apply and test different mathematical programming approaches and stochastic dominance analyses. Chapter 3 begins with some background information on the dairy sector in Kenya, the organisation of KARI's dairy research program, an overview of KARI's allocation of resources to its portfolio of research programs, and an outline of past program-level priority setting efforts. The subsequent sections report on the major details of the dairy program priority setting exercise, including the economic surplus approach used to calculate the economic gains from research, the measurement of the basic research parameters for technology generation and adoption, and presentation of the final evaluation results of the dairy projects identified and prioritised during this exercise.

Chapter 4 presents a critical assessment of the priority setting exercise from a methodological perspective, and identifies major shortcomings where the employment of enhanced formal evaluation and decision making methods can bring about major improvements. It follows the description of the potentials of different mathematical programming approaches to improved decision making, i.e., what type of decision problems in priority setting are amenable to mathematical programming models. In a next step, several aspects of risk and uncertainty are discussed within the context of agricultural research with a major focus on the importance of risk and uncertainty in research evaluation and how priority setting examples have dealt with risk and uncertainty in practise. The remaining sections of Chapter 4 present the Monte Carlo simulation technique as a formal method to enhance the economic surplus framework used in the case study towards a stochastic evaluation framework that incorporates, quantifies and generates insights into the riskiness of research projects. Finally, a summary of the results from Monte Carlo simulation is presented together with individual risk profiles for selected dairy research projects.

Chapter 5 constitutes the starting point for the development and application of mathematical programming models. First, a simple deterministic baseline model is developed that addresses the optimal allocation of research resources under a multi-objective framework. A first model application analyses the trade-offs between efficiency and equity objectives by defining different scenarios for the regional distributions of research gains. In further sections of Chapter 5 several model extensions are introduced, e.g., different budgeting strategies, constraints on research success, project interaction and project selection constraints representing typical decision constraints in agricultural research planning. Some types of model extensions are examined in more detail, e.g., by providing an outline of the mathematical programming syntax and developing and testing different decision scenarios.

Chapter 6 presents the stochastic dominance analysis as the major decision concept to comparison and prioritisation of research activities whose outcomes are uncertain and described as a probability distribution. The core of Chapter 6 is the development of "risk ranking tables" that synthesises stochastic dominance test results to a rank ordering of research projects and accounts for different decision makers' preferences towards risk.

Some further analyses are described that complement stochastic dominance in significant ways; these are: the analysis of the economic value of stochastic dominance, the determination of confidence intervals to examine the robustness of the stochastic dominance results using bootstrap procedures, and the application of the "synthetic outranking approach" that extends stochastic dominance to multi-attribute decision problems. Chapter 6 ends with some concluding remarks on stochastic dominance and Monte Carlo simulation and addresses some critical issues in practical application.

Chapter 7 describes mathematical programming approaches as decision aid in priority setting including risk and uncertainty. Common "risk programming techniques" are reviewed and evaluated. For demonstration purposes two different models are applied to the dairy research projects based on "utility efficient programming" and "quadratic risk programming" techniques with the main task of studying the implications of risk aversion and risk proneness on the optimal choice of research projects and the resulting economic gains. A further section examines the economic value that risk programming models may have over deterministic models through superior model results and improved decision making. In subsequent sections, the risk programming techniques are extended to the simultaneous treatment of risk and multiples by developing a multi-objectives utility efficient programming model. Application of this model examines the three-dimensional trade-offs between risk, efficiency, and equity.

Chapter 8 presents the general conclusions and outlines some implications for future research in research evaluation and priority setting.

2 Concepts and Methods for Priority Setting in Agricultural Research

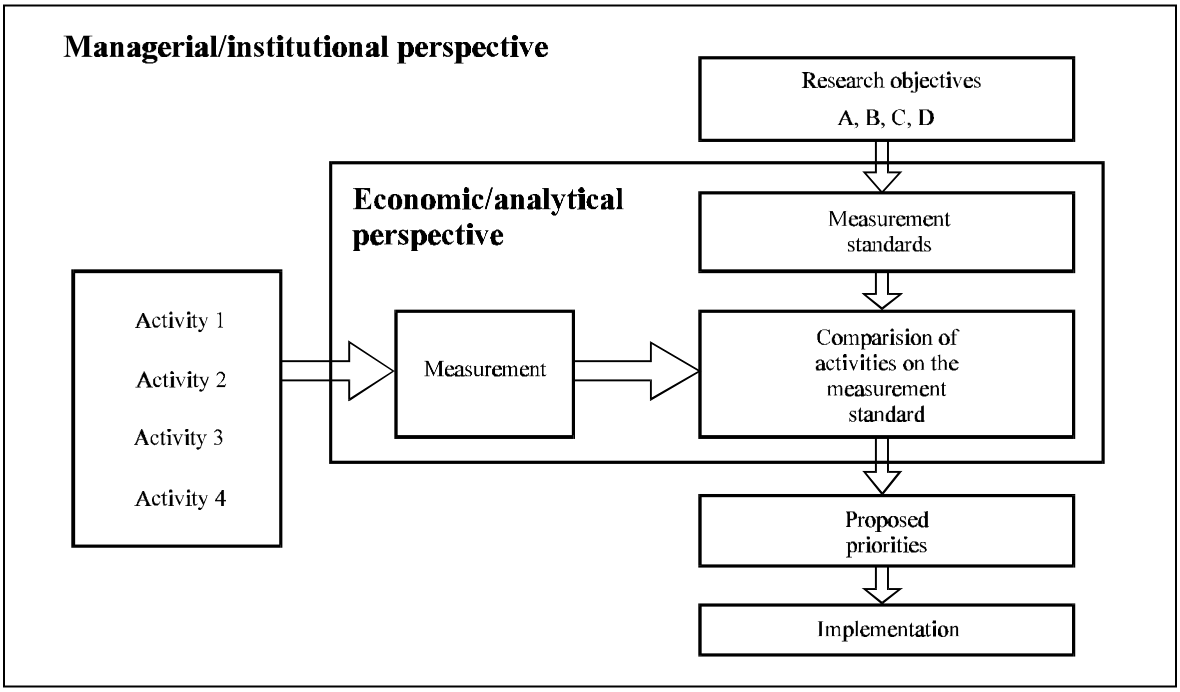
2.1 Principles of Priority Setting in Agricultural Research

Priority setting is a subject that has received great attention among research managers and planners during the last decade. Resources are becoming scare everywhere in public institutions. This is particularly so in developing countries. Consequently, resources need to be allocated in such a way that benefits from research are maximised for a given cost. This requires that choices be made between different patterns of research allocation. The rationale for doing this, and the procedures by which research activities are prioritised and resources allocated is the subject of this chapter. As JANSSEN (1994a, p. 2-3) points out, priority setting has an economic/analytical dimension which places emphasis on the methodological aspects of measuring the contribution of different research alternatives on pursued objectives, and the systematic comparison of these activities once the measurements have been defined. Priority setting may also be viewed from the managerial/institutional dimension which emphasises the process of arriving at a best possible set of research activities (see Figure 2-1).

The managerial improvement attributable to priority setting is manifold and its value can be well described according to JANSSEN (1994a, p. 11) as: "*First of all, it brings the people together that have a stake in the decision, thereby reducing the chance of personal bias. Secondly, it tries to build decisions on actual evidence, rather than on subjective assumptions. Thirdly, it requires clear and concrete thinking on what really matters, on why research is being done. Thereby it allows research managers and others to make up their mind and it provides clarity and transparency to personnel and other stakeholders of the institution. Formal priority setting improves the quality of thinking as much as the quality of the forthcoming decisions*."

From this definition it becomes clear that priority setting in not only a task that brings more objectivity into play when decisions on an appropriate research portfolio must be made (which may be the main focus of economists), but also is targeted at improving communication internally – between researchers themselves – and externally – between researchers, policy makers, extensionists and farmers. Priority setting has a number of additional benefits: it promotes the review of the existing resource allocation, and the establishment of better management information systems which also may improve monitoring and evaluation, and increases credibility towards the outside world. Priority setting is one major task in research planning although the two terms are used sometimes as synonyms. According to COLLION and KISSI (1995, p. 4) research planning is a much broader concept, covering not only priority setting itself but also planning for the development of research resources (human, physical, and financial), research policy making, and the identification of an organisational structure for the national research system.

Figure 2-1: Priority setting from a managerial/institutional perspective and from an economic/analytical perspective



Source: JANSSEN (1994a, p. 3)

Priority setting has many dimensions and depending on the discipline of the expert can be viewed from different angles. Economists see priority setting mainly as a problem of evaluating and comparing different research alternatives, defining appropriate objectives and criteria, assessing the contribution of alternative research activities to these objectives, comparing these outcomes and establishing a rank ordering. This view has been criticised by social scientists who often emphasise other aspects. For example, STEWART (1995, p. 115) raises doubts whether the purely economic view of public sector research and the utility of typical economic measurement methods (e.g. cost-benefit models) are legitimate. She suggests that priority setting is best understood as a systematic process, with outcomes determined by the incentives and inter-relationships of choices rather than by ex-ante impact evaluation. Therefore it is desirable to approach research priority setting as a problem in systems design to improve the understanding of the way in which institutional systems such as research institutions, through their modes of operations, set priority de facto. Consequently, systematic user-based, institutional and political models need to be developed and applied.

Priority setting is done on different hierarchy levels within a research system or institution. As a guidance for the reader, the following terminology of the different priority setting levels is used. In this study the term "research program" designates a coherent group of research activities, all relating to a specific field: this could be a commodity or a group of commodities, e.g., the rice program or the cereal program, an agro-ecological zone (e.g., the arid zone or the highland zone program), a production system (e.g., the pastoral or zero-grazing dairy program), or a production factor (e.g., agricultural mechanisation or fertiliser improvement program).

A research program may be subdivided into subprograms as in the case of a program involving several commodities or production systems. For example, a cereal program might cover millet, maize, and sorghum which would then be its subprograms. A rice program may include irrigated rice, floating rice, lowland rice, and upland rice subprograms according to the predominant production system. Alternatively, subprograms may describe different research themes when a research program involves only one commodity. In this case subprograms will be called "thrusts". For example, a wheat program may be subdivided into major thrusts such as plant breeding, crop management, or plant protection. Further, a thrust consists of a set of components that will be called "research projects". A research project consists of a set of concrete research activities (experiments or studies) that are carried out within a finite time frame, budget, and by specific scientific personnel.

Priorities can be set for the development of the agricultural sector in its totality against other non-agricultural development efforts (e.g., infrastructure, industry development), for sector-wide agricultural research against other public agricultural services, e.g., extension service or government price support, for nation-wide research programs on a commodity or factor, and even for projects within these programs. Priority setting levels mentioned in the context of a research system are usually the international, national and program levels.

At the highest level research priorities may be set on an international scale and involves decision on the allocation of resources to international research institutions (e.g., research centres of the CGIAR system), to research areas (e.g., agriculture, forestry, or environment), or to research programs and regions. One prominent example is the Consultative Group on International Agricultural Research (CGIAR) with its numerous research centres around the world. Priority setting and advise on resource allocation for the CGIAR centres is provided by an independent Technical Advisory Committee (TAC) that started with the first priority setting analysis in 1973, and has regularly continued this effort to date. More recently, GRYSEELS et al. (1992) have presented a priority setting framework for use by the TAC secretariat in allocating scarce resources among regions, commodities, and activities within the whole CGIAR system. Further, there are a few other examples where individual CGIAR centres with a multi-national mission statement of their research area have set priorities among different commodities and regions, e.g., ICRISAT as reported in KELLEY and RYAN (1995).

Priority setting in national agricultural research institutions requires decisions at, at least, two stages of planning: at the national level as long term and strategic planning among major commodities and factors of productions (may be every 10 years), and at the program level as short to mid-term planning among sets of research projects of the same program (may be every 3-5 years).[1]

Complications arise if a research institution is structured around nation-wide commodity programs on the one hand and regional research programs and centres on the other hand (JANSSEN 1994b, p. 12). For example, if priorities are set for a commodity program the consequences on the regional allocation of resources may not be compatible with the current regional research policy and the requirements of the regional centres. If priorities are set on a regional basis, the direction of a commodity program may be more influenced by the importance of the regions and presence of research facilities rather than by the potential impact on national production.

2.2 Procedures and Steps

Priority setting may be best understood as a process where partial tasks, methods, and outcomes are defined as individual working steps with each step building on the last. Several priority setting procedures were developed to serve as an organisational and controlling framework of the priority setting process. All these procedures differ in small details but the definition and sequence of the working steps are very similar. COLLION and KISSI (1995) have developed a procedure for program formulation and program-level priority setting which has gained widespread use and has served as the base for other modified approaches. COLLION's and KISSI's procedure distincts eight sequential working steps. Figure 2-2 outlines this procedure within which priority setting is defined in a narrow sense as only one step among many. In fact, practical application of priority setting on program level requires that all steps be worked through. The procedure combines analytical processes based on knowledge from various disciplines with more creative processes that require the input of people with different perspectives.

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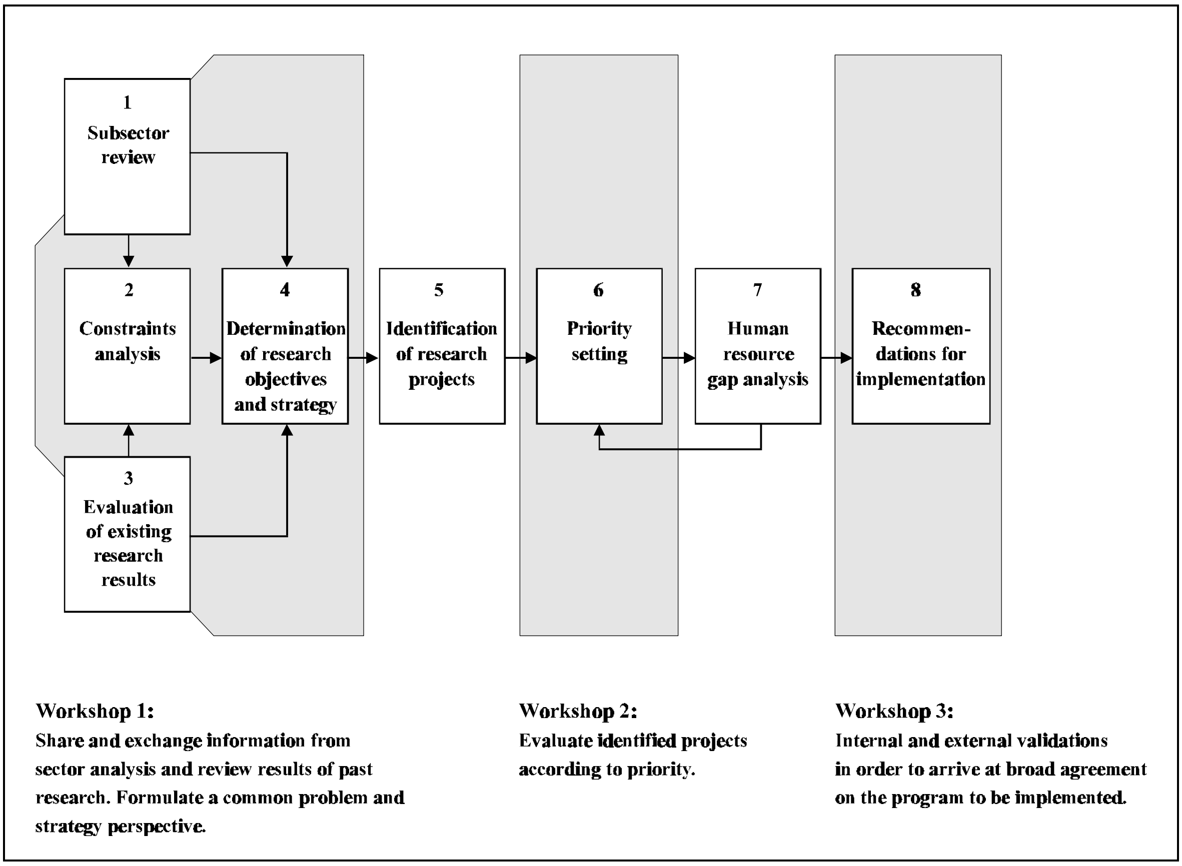
[1] However, inconsistencies regarding the notion of priority setting levels exists. For example, DAGG (1991) describes priority setting at program level as making choices between different research thrusts and defines planning for research projects as project level priority setting. A similar scheme to that of DAGG (1991) is also used by MILLS and KARANYA (1997), and MILLS et al. (1995).

As indicated in Figure 2-2, COLLION and KISSI (995) suggest to organise the numerous working steps around two or normally three workshops. Each workshop differs in the tasks to be accomplished, and may have a different audience according to the expertise required. The detailed description of the steps draws heavily on the papers by COLLION and KISSI (1995), and JANSSEN and KISSI (1997).

Figure 2-2: Steps in research program formulation and priority setting



Source: Compiled from COLLION and KISSI (1995 p. 7); JANSSEN and KISSI (1997, p. 7)

Step 1: Subsector review. This step provides a comprehensive overview of the subsector of the commodity at stake. The subsector review should contain two parts: One is an overview of the country's economy, the importance of the sector within the economy and the pursued development objectives; the other is the description of agro-ecological zones and production systems. By agro-ecological zone is meant a portion of land with a relatively homogenous production environment, normally defined by its climate, soils and slopes. Agro-ecological zones can be defined rather informally with experts or can be developed, for example, using GIS techniques. In contrast, the production system is related to the way farmers combine production factors. However, in many cases there may be certain overlaps between agro-ecological zones and production systems. The definition of agro-ecological zones are in most cases specific to the researchable factor or commodity under consideration. The subsector analysis should lead to a document that provides knowledge on the development objectives of the research program and the current situation within the agricultural sector. This document is an initial step and should be presented to the workshop participants at the start of the first workshop.

Step 2: Constraints analysis. In this step the information from the subsector review and the knowledge of the participants in the planning process is combined to define the technological and socio-economic constraints that impede the solution of a given problem and opportunities for research. This step ensures that the research program is based upon clearly defined and strongly felt problems and that the problems are not only seen from the scientist's point of view but also from an user and extension perspective. The breakdown of constraints into causes and effects can be accomplished by constraint tree methods and the use of visualisation techniques which allows participation of the whole group in a priority setting exercise. To develop such a network of causes and effect relationships is a preliminary step in defining concrete research activities that can best address the most urging and researchable constraints. How detailed a constraint analysis should be depends very much on the effort being spent on the definition of agro-ecological zones and production systems since constraints analysis builds on these two categories. At the end of the constraints analysis a set of information is derived including the types of constraints and proposed solution to these problems, the relative importance of the constraints, and the arrangement of the particular regional, zonal, or production specific problems.

Step 3: Evaluating past research. Before any effort on defining appropriate research projects are undertaken, it is useful to have an overview of what research has already been done so far in the different locations to address each particular constraint. The evaluation of the past and ongoing research should consider information regarding research results that are already spread to farmers, that are ready for dissemination or need to be validated on-farm. It should further include a critical assessment of what kind of research is unproductive, has a low chance of success, and what promising areas of research are currently not covered. Step 3 helps the research program to avoid duplication of previous work and increases the effectiveness of research projects. Information of past and ongoing research can be provided by annual reports; also, scientific publications are useful sources of information. If a management information system exists this may also be explored. When possible not only the institute's research activities but also external research from other institutions and countries should be reviewed so that it could be imported and adapted to local conditions. The possible import of external research needs to be recognised in the research plan especially if activities in the research program are cost-intensive.

Step 4: Defining research objectives. Once the constraints facing the research program are defined and an inventory of previous research achievements made, the research program may define the objectives it wishes to achieve during the planning period. Research program objectives can be directly drawn from the identified research opportunities as part of the information embodied in the constraint trees and can be organised as research objective trees. For example, when constraints analysis has identified insufficient provision of fodder during the dry season, it follows that a direct research objective will be to increase the fodder base in the dry season. Since constraints may be numerous, derived objectives may be too numerous to handle when later in the process the contribution of the research projects need to be assessed. Therefore, it is necessary to aggregate these low-level objectives to a limited set of broader defined objectives. Such broader objectives need to reflect the general economic and social objectives of a research institution. Often, the gap between the low-level objectives derived from technical constraints and the broader economic and social objectives is too large to bridge.

Therefore, the final research objectives are usually deduced from national development objectives, and redefined in more concrete terms by stakeholders of the research institution and commodity (see Chapter 3). Prominent high-level objectives in priority setting are efficiency, equity and sustainability. The efficiency objective states that research needs to contribute to increased productivity in agricultural production. Criteria for efficiency can be stated in monetary terms e.g., increased farm income or in technical terms such as the effects on yield increase or cost reduction. The equity objective mainly relates to the distribution of the efficiency gains between different groups or regions, e.g., between consumers and producers, farmers in different locations, farming systems, or between rich and poor farmers, gender, and so forth.

Sustainability is concerned with the preservation of the natural resource base, or more precisely, with the maintenance of the long-term productivity. Sustainability takes into consideration the fact that some technologies, although they may improve production in the short term, may have a long-term destabilisation effect on the eco-system and production environment. Because of its broad definition sustainability often needs to be expressed more specifically depending on the particular problems of the commodity and the agro-ecological zone with respect to sustainable production, e.g., soil fertility, soil erosion, bio-diversity ground water or salination problems. Apart from these three objectives several other objectives are prominent too, such as security objectives that are related to reliance on food imports or the nutritional status of poor households, increasing exchange earnings, or employment of rural labour.

Step 5: Identification of research projects. This step leads to a coherent and finite set of research activities which should completely cover all researchable constraints and objectives. For each research project, experts need to specify the required human resources e.g., the disciplines and number of researchers and the amount of research time, transportation and laboratory equipment, the location where research takes place – this may be a research station, laboratory, farms or a combination of these – and the likely duration of the projects to achieve preliminary results. Research projects do not need to be spelled out in great detail, but their overall shape and size should be visible.

Two types of projects may be relevant: First, technical projects that help to overcome specific constraints in production, and second, support projects – be they economic, social or from any other discipline – that can improve the scientific base of the technical projects and thereby increase their chance of success. Choosing the right level of aggregation is an important issue that needs to be considered when research projects are specified. When the level of aggregation is too low – e.g., projects are defined in very small units – they may become technically interdependent, such that the potential impact or costs of one project is influenced by other projects. When the level is too high projects may become too large and too unspecific such that the potential impact will be difficult to assess. Moreover, all projects may appear as essential which makes it impossible to set priorities among them.[2]

Step 6: Priority setting sets the stage for evaluating the potential contribution of the research projects identified in step 5 on the research objectives and criteria defined in step 4. The evaluation leads to estimates of the projects' returns described on a value scale, or described in qualitative terms with both serving as a basis for comparison and ranking research projects. Establishing a rank order for projects is necessary, because there will always be more projects in the list than can be implemented with the resources available. Whatever the procedure used priority setting is based on the perceived contribution of each project to the research objectives. Many methods are available for setting priorities, including several economic analysis methods, ranging from simple cost-benefit analysis to more complex economic surplus models. Other approaches include linear programming methods, scoring methods, the Analytic Hierarchy Process, and simple checklists.

All these approaches differ greatly in terms of data and resource requirements, as well as in the degree of participation they allow. Measuring the contribution towards research objectives mainly falls within the responsibility of a socio-economist, who, with the support

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[2] The same argument holds when research activities that need to be evaluated are not defined in terms of projects but in terms of broad research thrusts where the concrete content of these thrusts and the generated technologies are hard to conceive.

of the program leader, should design the approach, obtain the required data, calculate the impact estimates and present the results. The major challenge in priority setting is to assess, combine and compare the benefit dimensions. So, priority setting methods are required that can do this in a simple and straightforward manner. Once workshop participants have provided and validated their judgement on the different benefit dimensions that each project can be expected to achieve, benefits must be combined to assess the projects' contribution to the total benefit. By comparing the expected benefit with a cost indication for each project, it is possible to calculate which projects have the highest impact per unit cost. The ranking that results is then assessed and discussed by workshop participants in a plenary session. Assessment and ranking may be iterative and cyclical processes because assumptions may need to be reassessed, modified and included into sensitivity analysis so as to result in new priorities and plans until the final assumptions and results are widely accepted.

Step 7: Human resources gap analysis. Once the priority research projects are defined, the program should assess whether it is equipped to implement them. One major concern is whether the program has the right disciplinary mix of people. The human resource requirements are aggregated and then compared with the resource availability of the program. It is important to have established a human resource inventory of the research program, and eventually of the whole research institution. The difference between human resource needs and the current availability of them is the human resource gap. This must be filled by means of recruitment, transfer between research programs, or training. Gap analysis may reveal the need to revise the list of prioritised research projects, if the number of researchers required exceeds the resources allocated to the program, or if the necessary disciplinary skills simply cannot be found or generated.

Step 8: Recommendations for implementation. The purpose of the last step is to present decision makers with an outline of the measures that need to be taken to ensure that the program's priority projects can be implemented and research results adopted. Implementation may occur under one of two scenarios (JANSSEN and KISSI, 1997, p. 51): First, if the program focuses on a new research area, the activities to be carried out under the priority projects are implemented gradually as scientists are recruited or relocated to the new program and as financial resources are mobilised. If the program already exists and the priority setting exercise has served principally to reorient a program's direction, the priorities established must be reconciled with the projects already in progress. If ongoing projects match established priorities, they should continue and receive support until their completion.

However, if projects do not match priorities they should be stopped and assign new priority projects to the affected researchers. According to JANSSEN and KISSI (1997, p. 52) there are two exceptions where discontinuance of ongoing but not prioritised projects is not appropriate; when projects have been going on for quite some time and are close to completion – especially if projects have already consumed a large amount of resources set aside for its implementation – or when researchers work in projects as part of a thesis in preparation for an academic degree.

To ensure successful implementation, it is crucial to have both internal and external support for the shift in the program's direction. Program leader should therefore write a program document explaining why the program came about with a outline of the different working steps and results, and stage an internal validation workshop within the research institute to identify potential collaborators and assess the program's scientific merits. To gain external support, the program's outline should be made available to major stakeholders (external validation). In a final steps, staff members of the program need to develop research projects in more detail. This means identifying research methodologies, resource requirements beyond scientific staff and budget, as well as developing monitoring and evaluation mechanisms.

2.3 Common Methods for Priority Setting in Agricultural Research

2.3.1 Choosing the "Right" Method

The methodological aspects of priority setting have attracted much attention. A vast amount of publications deal with the development, empirical applications and reviews of priority setting methods and models.[3] Of the broad spectrum of methods that have been developed in the context of priority setting since almost 30 years ago, this chapter concentrates on the currently most prominent methods. Priority setting methods vary widely in their scope of analysis, degree of sophistication and applicability. They are often classified according to the number of objectives they can handle (single or multi-objective methods), the measurement concepts (direct and indirect, or qualitative and quantitative measurement), and the time dimension (ex-post and ex-ante) methods.

Despite this heterogeneity ALSTON et al. (1995, p. 464-465) point out "*that the same basic economic principles, concepts, data, and measures are relevant for all serious approaches to research evaluation and priority setting. While each approach may lie at a different*

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[3] For a review of some of the formal approaches used in research evaluation and priority setting refer to SHUMWAY 1973; NORTON and DAVIS (1981); RUTTAN (1982); CONTANT and BOTTOMLEY (1988); HORTON et al. (1993); and ALSTON et al. (1995).

point along a spectrum of varying detail and effort, they all rest on a single theoretical foundation. More elaborate approaches involve more sophisticated ideas and more complete empirical analysis. Simpler, shortcut methods, may be different in practise but ought not to be different in principle". The theoretical foundation must comprise the decision making context, especially when multiple objectives are present and need to be compared and aggregated, as well as the evaluation procedures that must include all relevant factors of research impact and put them in the right relationship for the overall contribution.

Given that there is no single best method that stands above all others, how can one make a good choice in selecting the "right" method which, following the "principle of parsimony" is as accurate as necessary but as simple as possible? In most cases, the more complex methods require greater cost and, accordingly, may not always be economically better, even though they may be perceived by some as "better" science. Research administrators and managers must exercise their best judgement on how to land on the spectrum of detail and effort. Moreover, the right point on the spectrum can differ widely according to circumstances such as the nature and scale of the problem to be investigated (the size of the research program, the numbers of research projects under examination), and the resources available for conducting priority setting exercises.

One major determinant for the choice of an appropriate method is clearly the category and type of research under investigation, as well as the type of research objectives on which research activities need to be assessed. There are several difficulties in applying formal methods for setting research priorities. CONTANT and BOTTOMLEY (1988, p. 4 ff.) examine this question in detail, and they see the most critical issue in the impact measurement problem.

Unlike industrial investments the effects of investments in agricultural research are hard to measure because of the multiple dimensions, the large time lag between technology development and application, various sources of uncertainties in the production and research process and many other peculiarities. The amenability of research to measurement varies according to the type of research project or program and the impact dimension. Efficiency gains (cost reduction or yield increase) are easier to assess than the distributional implications or the effects on soil, water or bio-diversity. Similarly, basic research and research on the natural resource base are hard to elaborate, if at all, in contrast to adaptive research or research within a commodity program (see Figure 2-3).

Most attempts in the past have concentrated on commodity programs where evaluation and priority setting is comparatively easy. A great challenge in developing quantitative methods to improve priority setting lies in extending the range of research activities and research objectives to which such methods can be applied.[4] Evaluation of non-commodity research such as research on production inputs, farming systems, natural resource base or social and economic research is faced with more difficulties than commodity programs. The major reason is that non-commodity research is less amenable to quantitative valuation, and has widespread and diffuse effects on several commodities. Also expertise of priority setting experts is rather limited.

However, some gradual differences appear among non-commodity research with respect to evaluation. Probably most accessible is research on the use of certain production inputs e.g., the use of fertiliser or pesticides when they are dealt with in conjunction with few commodities and its cost reduction effect. Also, research on labour and machinery could be studied on a whole-farm basis or from a commodity point of view. Research into components of the natural research base and sustainability research (e.g., soil, water, or climate) could be assessed by applying market or non-market valuation techniques (COMMON 1995, p. 153; GRAHAM-TOMASI, 1991, p. 97-98).

The essential difficulty with various aspects of sustainability is a poor feed back from observable and measurable results. Further, the base case outcome in the absence of sustainability research is much less easily defined than it is for commodity-based research (GRAHAM-TOMASI, 1991, p. 97). At the end of the scale lies social or economic research whose final measurable effects on the mode of production may be intractable. When assumptions become highly conjectural, measurement and comparison with other lines of research will no longer be reasonable. Thus, other, probably informal priority setting procedures need to be developed.

Figure 2-3 is a schematic representation of the influence of the different types and categories of research on the way decision making and impact evaluation can be dealt with. The type of decision making – whether formal decision analysis or heuristic approaches – is directly dependent on the type and precision of information generated from evaluation. Many formal decision analysis methods, for example mathematical programming models, require quantitative information, usually cardinal values on the returns to a research investment, e.g., net present value, internal rate of return or cost-benefit ratio. In reality the mixture of decision making and impact evaluation approaches is not as clear-cut as suggested in Figure 2-3. Often priority setting methods combine both aspects with different

[4] The measurement problem has been found less of an issue among the huge body of ex-post research investment studies because most of them have dealt with commodity programs and evaluation has concentrated on economic returns rather than on non-economic benefits.

rigour. For example, economic surplus methods offer a great variety and detail in the calculation of the economic returns to research but are rather weak on the decision making side. In contrast, the Analytic Hierarchy Process is able to get along with a basic set of qualitative information regarding research impact but has its strength in ranking research objectives and activities according to their relative priorities.

Figure 2-3: Priority setting methodologies for different research types and program categories

Type of research				
Basic research	Strategic research	Applied research	Adaptive research	
Research program category				
Social and economic factors	Natural resource base	Farming systems	Production inputs	Commodity research
Approaches to decision making				
Heuristic approaches	←	→		Formal decision approaches
Approaches to impact measurement				
Qualitative approaches	←	→		Quantitative approaches

JANSSEN (1994a, p. 3) argues that the choice of a priority setting methodology depends on the type of problem that has to be solved, the type of people that are involved in the priority setting process, and the implications that are linked to the outcome. As a guidance to research management he proposed the following six criteria.

Transparency: Participants and decision makers must have an understanding of the measurement and valuation concepts and their underlying assumptions, as well as how the final results have been obtained. If they cannot understand the logic and arguments and the way how results are assembled to obtain the conclusion they may well be reluctant to accept the outcome.

Participation: The methodology must allow the participants to take an active role in the whole priority setting process and to communicate and exchange ideas and knowledge. It is also important to include the final clients of the research. Thus methods that support participation should be favoured.

Simplicity: It makes the method more easily applicable. Simple methods generate fast results and do not discriminate against people who are largely inexperienced in priority setting. Simplicity also means more generality, thus, it can be applied to more situations.

Theoretical logic: Theoretical correctness should not be a point of discussion, but may be seen from a different point of view. Agricultural economists may recommend that the method used should be in concordance with modern decision theory and should incorporate whenever possible the market dimension i.e., the definition of supply and demand functions. Decision sciences will emphasise the different dimension of research to be taken into account and that group decision making is recognised while research management will emphasis that priority setting should provide the guidelines on how the proper plan for the implementation of the priority setting results can be accomplished.

Discriminating potential: This means methods should discriminate good from bad decision alternatives and should provide clear insights into the key determinants of performance.

Cheap to apply: A priority setting exercise competes with the institute's resources that could otherwise be invested in research. So, priority setting should always have a positive pay-off which means that the improved quality of decisions should be able to make up for the costs and the scarce time of the scientists.

It is clear that these six criteria mentioned above are not equally important. Theoretical logic of course is imperative for any priority setting method. For other criteria e.g., costs to apply and transparency, there is possibly more room for compromises. No attempt is made here to assess priority setting methods on these criteria because of the inherent subjectivity. Instead, the remaining section introduces six major methods including the outline of the basics principles, the advantages and disadvantages as well as some references to practical applications. The description of the different research evaluation and priority setting methods does not include the "production function approach" since it has only been applied to ex-post "returns on investment" studies but not to ex-ante priority setting. Interested readers are referred to ALSTON et al. (1995, chapter 3) and the numerous references cited there.

2.3.2 The Precedence and Congruence Method

Precedence and congruence are two prominent approaches with widespread application in research allocation decisions. The precedence approach advocates that previous funding should form the base for allocating funds in the next year for research projects or regions. Funds can then be increased or decreased in small proportions (ALSTON et al., 1995, p. 488). The major advantage of precedence lies in its long-term continuity in the funding which conforms well with the long-term nature of research investments. On the other hand, precedence preserves a situation of constant relative emphasis on each research category or region regardless of the returns to research. This makes it inherently more difficult to trigger innovate research policies with new regional orientation and research activities. Due to the fact that precedence ignores any determinants of research pay-offs – neither on the cost nor on the benefit side – there is no guarantee that decisions on the allocation of resources are optimal in view of a most efficient use of resources. For these reasons some authors seriously question the validity of precedence for making allocation decisions. As VON OPPEN et al. (1992, p. 39) put it "*there seem to be no significant difference between a decision based on precedence and the absence of a decision*". In view of this, there is some indication that precedence is not going to play a significant role in future research allocation decisions.

Congruence (or parity model) means that research funds should be allocated to commodities in the same proportion as their production values, assuming other things are held equal. If, for example, the value added to commodity *a* is twice as much as that for commodity *b* then commodity *a* should receive funds twice as much as commodity *b*. Congruency can also be stated in terms of the ratio of the commodity's share on the value produced to the share on research funds. According to this definition, a congruency index can be computed that indicates how well funding pattern and value added are in accordance with the congruency rule. CONTANT and BOTTOMLEY (1988, p. 11) define the congruence index *CI* as:

(1) $$CI = 1 - \sum_{i=1}^{n} (A_i - S_i)^2$$

where A_i is the share of a particular commodity in the research budget, and S_i is the share of that commodity in total value added. If the proportion of the research budget is perfectly in line with the proportion of the value added, then *CI* takes the value 1. The greater the mismatch between the budget and value added the smaller *CI* becomes. Congruence can serve as a gross indicator and can provide a base for comparing the existing allocation of resources to research on different commodities or regions with the importance of these commodities' and regions' contribution to national income. If there are widespread discrepancies in this respect, these can be looked at and discussed among research stakeholders.

Congruence constitutes an improvement over precedence in that it explicitly considers research costs and value of production as two major factors of the net benefit of research. Congruence has some further advantages: it is conceptually simpler, addresses directly the allocation of research resources, which should always be the major focus in priority setting exercises, and requires fewer inputs namely production values for different commodities and regions that can be easily gathered from national income and trade statistics. Information on research costs world-wide are less abundant but there is steady improvement through improved budgeting activities in national and international institutions.

At first sight, congruence as a rule for allocating research resources seems to be intuitive since research funds should flow towards commodities that are of high economic importance. But it tends to maintain the status quo: today’s core commodities get the most funds while commodities currently less important or not yet produced receive only a minor share or nothing even though research investment may promise high returns. As with precedence, congruence is not favourable to inducing and supporting innovative research efforts and breakthroughs.

The congruency rule can be applied to compare resource allocations by commodities, research areas, production stages or by disciplines either for each dimension alone or in combination (ALSTON et al., 1995, p. 489). Several studies have used the congruence rule to make recommendation on the allocation of research resources (e.g., PINSTRUP-ANDERSON, 1982; EVENSON et al., 1979). Other studies (e.g., KIRSCHKE, 1986) have examined how well the current allocation of research resources is in line with the congruence rule. KIRSCHKE (1986) also examined the validity of the congruency concept as a normative decision rule for the allocation of research funds and applied this to the International CGIAR system. He showed that only under the premise of equal research elasticities between commodities is the congruency concept in line with the optimality condition for the allocation of resources. With research elasticity is meant the percentage change in value added in relation to a percentage change in the research budget. This implies, the greater the differences in the commodities' elasticities is the less suitable is the congruence rule. In situations where the response in production to increased research resources is unknown, then one can assume research elasticities to be equal. If there are indications of strong discrepancies in the commodities' research elasticities, the congruence rule should be modified according to KIRSCHKE (1986, p. 14) as:

(2) $$\frac{\frac{a_i}{v_i}}{\frac{a_j}{v_j}} = \frac{e_i}{e_j} \quad \text{or} \quad \frac{a_i}{a_j} = \frac{v_i \times e_i}{v_j \times e_j}$$

with e_i = research elasticity with respect to a particular region or commodity,

a_i = research costs with respect to a particular region or commodity, and

v_i = value added or initial value of production for a particular region or commodity.

The optimality condition requires that the share of research budget for two commodities should be proportional to their product of the elasticities weighted by the value added. If for example a 1 per cent increase of the research budget for commodity *i* and commodity *j* would result in a production increase of 1 per cent for commodity *i* and 2 per cent for commodity *j*, and given that both commodities have the same value added, then the optimality condition would indicate that the share of research budget should be twice as high for commodity *j* as for commodity *i*.

Apart from the normative quality, congruency has other important shortcomings. It is largely restricted to the commodity level and cannot be used to set relative priorities within a research program that is not directly related to a particular commodity. Finally, congruency ratios offer no help in the determination of the overall size of the research budget. Therefore, congruence should be seen only as a rule of thumb and as a starting point for the allocation of research resources, unless reliable information on research elasticities becomes available.

2.4 Scoring or Weighted Criteria Models

A ranking approach which formally incorporates the decision maker’s subjective trade-offs and decision criteria into a model framework is known as a scoring model. A primary assumption is that a few criteria can be established which, when properly related, will specify the desirability of a decision maker’s alternatives. The set of criteria can consist of both quantitative and qualitative criteria so long as each is independent of the other. Then a discrete scale is developed for each criterion with sufficient range to include all projects for which an evaluation is desired. An overall project score is calculated generally by summing the product of criteria weights and scores over all criteria.

The basic idea of scoring rests on a multi-criteria decision matrix as outlined in Table 2-1. A decision matrix consists of the decision alternatives A_j, decision criteria C_i, criteria weights w_i as a measure of the relative importance of the criteria, and the measures R_{ij} defining the contributions of the decision alternatives A_j to each criterion C_i. For every decision alternative A_j, the measures R_{ij} and the criteria weights w_i are combined to the final scores U_j on which projects are compared and ranked to arrive at a hierarchy and priority order for implementation. Technically, such a scoring model can be seen as a special case of a multi-attribute value model with a deterministic and additive decision structure while the additive value function is composed of the final criteria scores.[5] Criteria weights are often normalised by restricting their values within the range 0 to 1 such that all weights sum up to 1. A serious problem with criteria and criteria weights is that the units of the estimates R_{ij} are usually incompatible with one another, even for different criteria related to the same objective. Therefore, if weights are attached to them directly on R_{ij} , the choice of units for criteria can dominate the weighting and distort the resulting ranking in unintended ways as ALTSON et al. (1995, Appendix A 7.1) have demonstrated.

Table 2-1: Decision matrix of a multi-criteria scoring model

	Criteria	C_1	C_2	C_3	...	C_n	Final score
	Weights	w_1	w_2	w_3	...	w_n	
Decision	A_1	R_{11}	R_{21}	R_{31}		R_{n1}	$U_1 = \sum_{i=1}^{n} R_{i1} w_i$
alternatives	A_2	R_{12}	R_{22}	R_{32}		R_{n2}	$U_2 = \sum_{i=1}^{n} R_{i2} w_i$
	...						...
	...						...
	A_j	R_{1j}	R_{2j}	R_{3j}	...	R_{nj}	$U_j = \sum_{i=1}^{n} R_{ij} w_i$

Source: Modified, after SPRINGER-HEINZE (1994, p. 133)

One possibility to circumvent the problem of the sensitivity to units is by weighting the rankings corresponding to the numerical values of the criteria rather than weighting the actual values R_{ij}. But this actually eliminates the cardinality of the values and its conveyed information to decision makers. Furthermore, weighting the rankings abolishes the possibility of using the final scores as input in other formal decision analysis methods, e.g.

[5] To comply with the multi-attribute (or multi-objective) decision theory, decision criteria in scoring models should hold preferential independence (KEENEY and RAIFFA, 1993, p. 107). For example, preferential independence is violated when criteria have an overlapping meaning.

optimisation models. An alternative to rankings is to normalise the criteria values by changing the value scale to a range between 0 and 1. Normalising will reduce or at least conceal problems arising from gross disparities in units while preserving the cardinality of the value scale. Among all three possibilities, normalising criteria may be the best alternative and has found widespread use in empirical applications.

To apply scoring, criteria must be defined and weighted. ALSTON et al. (1995, p. 474), and NORTON (1993, p. 164) distinguish two procedures for dealing with multiple objectives (criteria) and weights. One is to collect all information and conduct the measurement without a direct prior elicitation of weights. For the beginning one may place all weights on the efficiency objective, then generate the ranking and choose the set of projects. In the following step, the implication of placing incremental weights on non-efficiency objectives can be examined by comparing their efficiency outcomes. This way, the analyst may demonstrate the opportunity costs of using research for non-efficiency objectives. Unless efficiency is measured by economic surplus or cost-benefit analysis the efficiency trade-off in a scoring model is strictly qualitative, hence, there is no direct opportunity cost interpretation.

A second possibility is to elicit initial objective (criteria) weights by appropriate means and, after that, to proceed with all other steps. Then sensitivity analyses can be carried out for a different mix of objective weights and resulting changes in ranks and objectives outcomes can be analysed. The first method places major emphasis on providing information on the trade-off between objectives while the second method, which is most commonly practised, is more concerned with the provision of a concrete ranking and a list of research activities.

Scoring models produce a different set of decision alternatives under limited resource availability than formal optimisation procedures. This is not specific to scoring model, but is true for any other method that produces a rank ordering and selects decision alternatives by moving down the ranking list. Table 2-2 outlines a simple example to show the differences between solutions from scoring models and optimisation models, e.g. MP. It can be shown that scoring models do not always generate optimal solutions. The decision problem in Table 2-2 is to chose among three different decision alternatives given a limited budget of 100 Mio $US to be available for implementation.

Table 2-2: Selection of decision alternatives in scoring models compared to optimisation models

	Budget used (Mio $US)	Final score (a)	Final score per unit budget use (b)	Selection of decision alternatives from a scoring model		Selection of decision alternatives from an optimisation model	
				Ranking criteria		Optimisation criteria	
				(a)	(b)	(a)	(b)
Decision alternative 1	100	1000	10	X			
Decision alternative 2	50	800	16		X	X	X
Decision alternative 3	40	300	7.5			X	X

A scoring model would propose decision alternative 1, if the ranking list is based on the final scores (a), and recommend decision alternative 2, if ranks are based on the final scores per unit budget used. An optimisation approach, e.g., a linear programming model, would lead to a different set of decision alternatives, namely alternatives 2 and 3. In both cases the selection of the scoring model is suboptimal because of lower scores and higher budget use (a), and the large amount of budget which is left idle (b).

Numerous applications of scoring models are documented in the literature with varying degrees of sophistication concerning the measurement of the economic gains from research, and the number and types of non-efficiency objectives considered. To cut across recent applications, at least two or three non-efficiency objectives appear to play an essential role: these are "equity" either expressed on a regional basis or for social target groups, several aspects of "sustainability" as well as "food security" issues that take the form of improving the nutritional status or reducing the dependence of food imports. Economic impact assessment ranges from simple subjective scores to simplified cost-benefit analysis (e.g., COLLION and KISSI, 1995; CESSAY et al., 1989), complete cost-benefit analysis (e.g., KELLEY and RYAN (1995), economic surplus models and other approaches (e.g., for the CGIAR system, GRYSEELS et al. (1992) applied a modified congruence index as part of an efficiency index in a scoring model).

Simple scoring models do not require advanced quantitative and economic skills, and they can be used to rank long lists of commodities or programs. Through its simplicity scoring models can be easily set up in spreadsheet form and adjusted to new situations. They also promote broad participation in the priority setting process. As more sophistication comes into play all these advantages may be partially reduced. Scoring models are particularly useful when objectives are numerous and different types of quantitative and qualitative information must be combined and compared. Since scoring models are based on rough approximation of research contributions, they are particularly useful when data, time, and analytical capacity are limited. For this reason, they may be especially helpful in small research systems that do not have the resources for more complex economic approaches or when the data base of the commodity or production system concerned is rather poor (e.g., FRANZEL et al. (1995) used a simple scoring model for multi-purpose trees).

Another advantage is that scoring can be easily combined with other approaches such as cost-benefit, economic surplus or even with mathematical programming models. A strong focus on the "supply side" of research can be achieved when the economic efficiency index is derived from a cost-benefit analysis or economic surplus approach while the multi-criteria framework is kept tractable. This way one can combine the advantages of scoring with a strong measurement component. On the other hand, combing scoring with mathematical programming models allows the incorporation of various decision constraints other than budget and performing portfolio analysis by formal optimisation procedures. Objective function values in a mathematical programming model could be the final program scores aggregated over all criteria or can be individual criteria scores which would further allow a variety of trade-off analyses between conflicting objectives. A prerequisite is that the cardinality of the scores is preserved.

However, scoring models as commonly applied have been misused on several occasions and have violated many of the principles of research evaluation and priority setting (ALSTON et al., 1995, chapter 7). One frequent shortcoming is the use of poorly defined and overlapping criteria which arises when objectives and criteria are quickly stated and not checked for internal logic and consistency. As ALSTON et al. (1995, p. 470 ff.) point out, this commonly occurs between criteria that all relate in some way or another to efficiency. Criteria that are often used simultaneously are the value of production per hectare, number of hectares, foreign exchange earnings, likelihood of research success, adoption rate, and the like. For example, the CGIAR priority setting study reported by GRYSEELS et al. (1992) included both the value of production and usable land as separate criteria. However, these two criteria are in fact highly correlated and both pertain to efficiency.

The consequences are that such overlapping criteria provide a less accurate approximation to economic surplus through double or triple counting of the same effects; they violate the preferential independence axiom in multi-criteria decision theory and finally have a detrimental effect on communicating the fundamental economic issues in research evaluation by confusing economic parameters and functional relationships.

Another shortcoming is the ad-hoc elicitation of criteria weights which makes them highly subjective. There is always the possibility that the personal judgements which lies behind the determination of weights and scores may result in misleading conclusions. For example, decision makers tend to overweight program costs because of the constraints of the institute's budget which they must adhere to. In so doing they may overlook the likelihood that returns to research can outweigh costs by far. In fact, if costs and returns are defined as separate decision criteria they should be given the same weight because both belong to the same efficiency criteria.

Based on these findings, a consistent scoring model would require: first, a careful selection of important and independent objectives and criteria; second, a careful assessment of criteria weights, probably by using elicitation techniques like the Analytic Hierarchy Process instead of conducting ex-post "freewheeling" sensitivity analyses on criteria weights (ANDERSON, 1992, p. 1112); and third, the careful combination of subjective information from non-efficiency objectives with quantitative information from the efficiency objective, probably by normalisation of the impact values R_{ij} .

2.5 The Analytic Hierarchy Process

A promising but often overlooked alternative to scoring models is the Analytic Hierarchy Process (AHP) developed by SAATY (1980). A variety of applications have been reported in the literature ranging from planning, marketing, transportation to resource management and several other fields (PETERSON et al. 1994a). Some applications concern the selection of research activities in the private industry e.g., LOCKETT et al. (1986) for medical research, while no example has been reported for agricultural research (ISNAR and IHW/ETH, 1998, p. 8). The AHP is described by SAATY and VARGAS (1991, p. 14) as " ... *a multiobjectives, multicriteria decision making approach which employs a pairwise comparison procedure to arrive at a scale of preferences among a set of alternatives. To apply this approach, it is necessary to break down a complex unstructured problem into its component parts and arrange these parts, or variables, into a hierarchic order*“. Using the AHP for solving a decision problem involves four steps (ZAHEDI, 1986, p. 96):

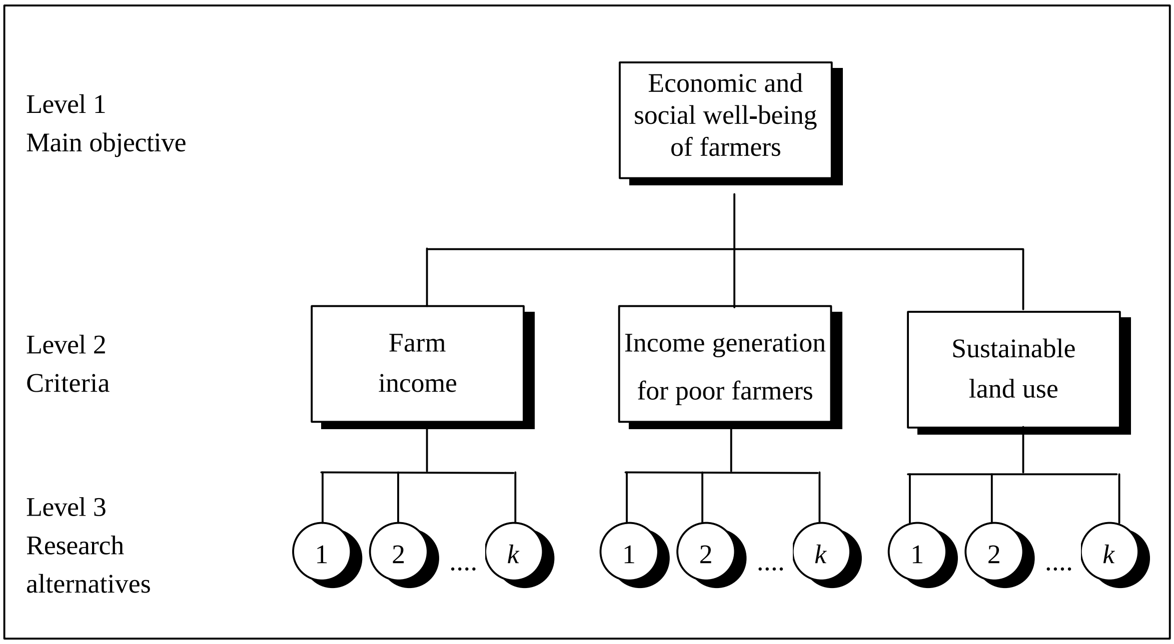
- setting up the decision hierarchy by breaking down the decision problem into a hierarchy of interrelated decision elements (criteria and decision alternatives);
- collecting input data by pairwise comparisons of decision elements;

- using the "eigenvalue" method to estimate the relative weights of decision elements (local priorities of criteria and decision alternatives); and

- aggregating the relative weights of decision elements to final cardinal priorities to arrive at a set of rankings for the decision alternatives.

Figure 2-4 shows a simple example of how a priority setting problem among a finite set of research alternatives could be described and transformed into an AHP framework. The example defines three hierarchy levels, with the first two levels defining decision objectives and criteria and the bottom level containing the set of research alternatives. The research alternatives are then compared in pairs to assess their relative preference with respect to each of the criteria at the next higher level. Similarly, the criteria are compared in pairs to define their importance with respect to the overall objective.

Figure 2-4: Structure of an AHP model for research evaluation and priority setting



Comparisons are made on a ratio scale and can be expressed either in term of values between 1 and 9 or in terms of verbal comparisons (equally important, more important, strongly more important, extremely more important, etc.). The advantages are that pairwise comparison can be based on hard data as well as on subjective judgement. Further, it is widely acknowledged that assessment of decision alternatives by pairwise comparison yield more reliable results than direct assessment of local priorities (weights) to all criteria levels and alternatives. Thus the AHP reaches a high level of accuracy with respect to the relative performance of decision alternatives.

Unique to AHP is that it recognises and locates possible biases and inconsistencies of the expert's subjective judgements by calculating a consistency ratio from the eigenvalue vectors of the input data. When applying the AHP for research priority setting, however, some critical issues should not be overlooked. The first issue is that the AHP, as is generally true for all methods that uses ranking as a guide to selecting decision alternatives, does not provide insights into how much resources should be spent on the different research alternatives nor can it include other decision constraints than simple research budget. The second issue comes into play when the decision problem encompasses many elements either as numerous decision alternatives and/or criteria. If one is not able to group criteria together or reduce the number of alternatives by pre-selection, then pairwise comparisons easily mushroom in number and become a time consuming and tedious procedure. Instead, one can reduce the problem by the use of the absolute measurement mode, the so called "rating". Rating refers to the direct assessment of the local priorities and can be applied as an alternative to pairwise comparison which substantially reduces the time requirement for the participants.

As mentioned by ISNAR and IHW/ETH (1998, p. 11) the use of rating implies a qualitative loss in expert judgement and generates less reliable results. The argument against direct rating is that decision alternatives and criteria are often too abstract for the evaluator to assign direct values while pairwise comparison on the other hand gives the evaluator a much better basis on which to reveal his or her preference. Also, the internal consistency of the assessment cannot be checked. Therefore, it is important to define the optimal relation between the two measurement modes and use rating probably for the less important alternatives while pairwise comparison should always be applied to the most promising prospects. As soon as direct rating becomes the predominant measurement mode, the AHP turns in fact into a simple scoring model. Another possibility as reported by ISNAR and IHW/ETH (1998, p. 11) is the use of an incomplete pairwise comparison technique which reduces the elicitation effort by stopping the process when the added value of questions decreases below a certain level.

A further problem that needs to be addressed is the intrinsic multiplicativity of some decision criteria. For example, when assessments must be made on some efficiency impact parameters such as change of research success or successful adoption, treating them as separate criteria in an AHP model would violate the multiplicative assumption since the AHP combines local priorities in an additive manner to arrive at global priorities. The problem can be solved by including additional hierarchies, one for each multiplicative parameter, and by combining the selective outcome of the hierarchies (ISNAR and IHW/ETH, (1998, p. 5).

As the few examples suggest, the potential of the AHP as a tool for evaluating research alternatives and decision support has not been fully exploited as yet. There are strong arguments in favour of the AHP as the better methodology compared to simple scoring models. Although problem setting and treatment of multiple criteria are similar between the two methods, the pairwise comparison of decision alternatives promises far better and reliable judgements by participants than does direct elicitation in scoring models. The AHP is well suited to be combined with other methods. For example, in combination with scoring models the AHP could be selectively used for elicitation of criteria weights which constitutes a critical factor for the accuracy and validity of scoring models. In combination with formal optimisation, the AHP could serve as an assessment procedure with the provision of local or global priorities as objective function values that are fed into a multi-objective programming model. An example of the use of the AHP in combination with a mathematical programming model is documented in PETERSON et al. (1994b).

2.6 Economic Surplus and Cost-Benefit Analysis

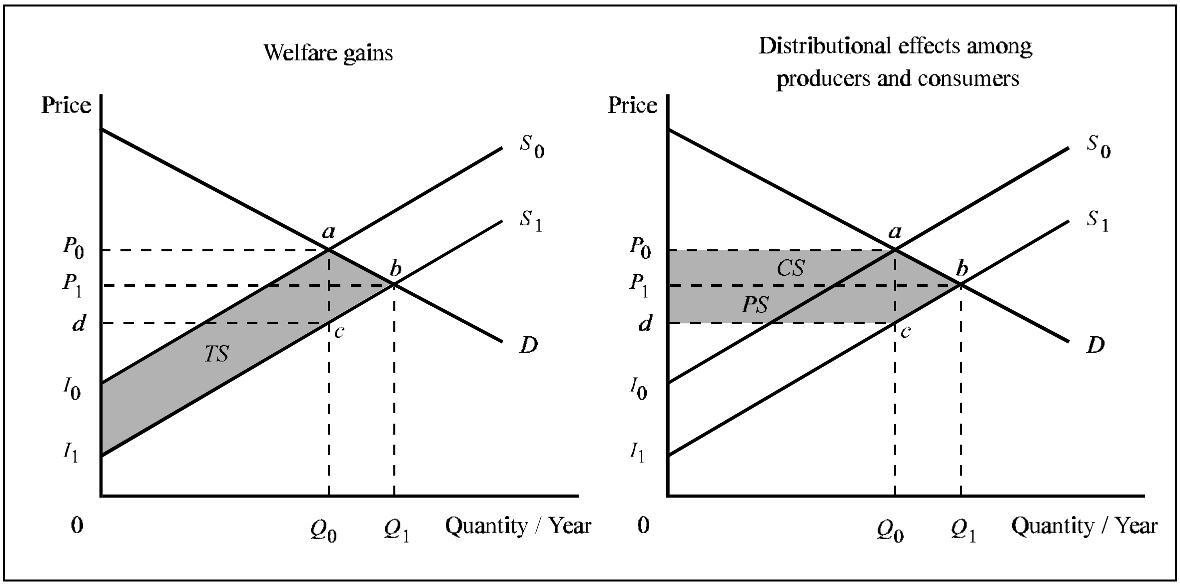
Cost-benefit analysis and economic surplus derive their rationale from welfare analysis. Cost-benefit analysis is a widely used evaluation method used by governments and funding agencies for decisions on investments in developing projects. It is the major investment analysis method and is based on the concept of discounted cash flows taking into account the time dimension of the flows of costs and benefits of an investment. The main difference between cost-benefit and economic surplus is the way how the benefits from research investments are derived. Cost-benefit analysis values the research induced efficiency effect on yield increase or cost reduction at constant market prices, thus, potential market effects due to the changing supply schedule are not counted for.

The economic surplus approach uses a market framework to derive research benefits within which research outcome causes a rightward shift in the supply schedule. The economic gains are then calculated as the surplus accruing to producers and consumers which results from changes in the price and quantity of the commodity. By aggregating research benefits over time in cost-benefit analysis and economic surplus and comparing this with the costs for a research alternative one can calculate summary measures such as the net present value, internal rate of return, or cost-benefit ratio to compare and rank a set of different research projects. In agricultural research both methods have been applied in ex-post and ex-ante studies to calculate the economic returns from research investments.

2.6.1 The Economic Surplus Method

The economic surplus method derives its economic gains from research through a market framework within which the adoption of new technologies as research outcome is depicted by economists as a rightward shift of the supply curve. The left-hand side in Figure 2-5 illustrates the technical change in an economic surplus model by the rightward shift of the supply function from S_0 to S_1. This results in a new equilibrium price and quantity P_1 and Q_1. The economic benefits due to the supply shift are represented by the shaded area a,b,I_1,I_0. In case of a parallel supply shift and linear supply and demand functions, the shaded area a,b,I_1,I_0 is equivalent to the area a,b,c,d,P_0. In general, consumers gain from the adoption because they can consume more at a lower price (the increase in consumer surplus is indicated by the area a,b,P_1,P_0 as shown in the right diagram of Figure 2-5), and producers gain (the increase in producer surplus is equivalent to the area b,c,d,P_1) because their unit costs fall although they are faced with a lower price. The size and distribution of the research benefits among consumers and producers mainly depends on the magnitude and nature of the supply shift as well as on the price elasticity of the supply and demand functions.

Figure 2-5: Assumptions on markets of the economic surplus method



The shaded areas indicate the economic gains from research.

Source: ALSTON et al. (1995, p. 41, 60)

The literature is cluttered with controversy over the functional form of supply and demand functions, the nature and the market context of such research induced shifts (e.g., LINDNER and JARRETT, 1978, 1980; DAVIS, 1981). The absolute size as well as the gainers and losers from agricultural research are determined by such theoretical matters. In relation to total benefits, the functional form and price elasticities are relatively unimportant compared with the nature of the supply shift i.e., whether a parallel, pivotal or some other shift occurs. In relation to the distribution of benefits, the functional forms are relatively unimportant compared with the sizes of price elasticities and the nature of the supply shift.

It is very hard to predict the nature of those supply shifts (ROSE, 1980) and, at the same time, reliable estimates of the functional forms and elasticities are not always available. Thus, when estimating the benefits from agricultural research using economic surplus, errors are inevitably introduced by the assumptions regarding the market parameters which may lead to incorrect estimates not only in the absolute size of the research gains but also in the distribution among producers and consumers. Moving from a given shift of the supply curve to the evaluation of the benefits, there are several key components to consider. The core of such a relationship are the variables which determine the size of the shift in the supply schedule, sometimes represented vertically (when expressed as the cost reduction effect) or horizontally (when expressed as the yield increase effect). Such variables are often called *k*- factors and consist of the expected research success, the adoption rate, and the potential proportional yield increase or cost reduction given full adoption. The product of these *k*- factors determine the proportional supply shift which is then multiplied by the initial market price and quantity. Further procedures include the aggregation of annual benefits and the choice of an appropriate discount rate for converting future benefits and costs into present values.

Despite its mathematical complexity and high data requirement, economic surplus has experienced widespread application in the assessment of research gains on specific commodities and research programs. A detailed overview can be found in ECHEVERRIA (1990), and DANIELS et al. (1990). Many studies deal with a single commodity and apply rather simplistic market models such as that outlined in Figure 2-5. Here, special attention is deserved by some examples of more advanced economic surplus models. One example is the work from Davis, Oram, and Ryan (DAVIS et al., 1987) on setting priorities on the international level using economic surplus couched in a multi-product and multi-country trade model. On the national level there are several examples where economic surplus was applied to set research priorities for commodity research programs using intra-country or regional trade models (e.g., MILLS, 1997; MILLS et al., 1995).

The market framework developed by Davis, Oram, and Ryan (DAVIS et al., 1987) was designed to measure the ex-ante economic gains from commodity research and regional research activities for international institutions such as the CGIAR centres. The model provides a large set of quantitative information on the welfare gains accruing to different commodities and regions thus allowing the possibility of making recommendations on the choice of particular commodities or regional research portfolios.[6] The preceding market model framework allows differential probabilities of research success and adoption levels amongst commodities and regions to condition the expected economic benefits for alternative strategies and the distribution of these benefits among consumers, producers, importers and exporters. One specific feature of this model is that it enables inter-country or inter-regional (intra-country) spillover effects to be explicitly incorporated.[7]

MILLS (1997), and MILLS et al. (1995) applied a similar model to calculate ex-ante welfare gains for commodity programs in Kenya including the spatial dimension of research impact by subdivision of the whole research area into homogenous production zones (eco-zones). This model incorporates regional price spillover but does not include research spillover. When spillover effects are accounted for in a multi-region model, the distributional consequences of the economic gains for each region differ markedly. In general, price spillover reduce the economic gains especially for regions with a relatively large production share but with a relatively low *k*-shift value in the supply schedule. This is because reduction in the market price leads to large losses in producer surplus which outweigh gains in consumer surplus. Other regions may be favoured, especially those that exhibit large supply shifts (with a high adoption rate), and are net consumption regions. An interesting feature of a trade model developed recently (MILLS, 1997) is the possible conversion of price relations across regions. Normally, most trade models assume a constant price wedge between

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[6] Details of this trade model are described in DAVIS et al. (1987); RYAN and DAVIS (1990). Several other studies adopted this multi-market model to set priorities on the national level, e.g., PARDEY et al. (1991) for Indonesia.

[7] Spillover effects of research can stem from two sources:

- the applicability/transferability of research results targeted for one country can spill over into other countries or regions (technology or research spillover effect); and
- new technologies can affect prices not only in the region and country adopting the technology but in other regions and countries where the product is consumed and produced (price spillover or price transmission effect).

Price spillover effects are inherently incorporated in an economic surplus framework while research spillover are not. These spillover effects influence both the size and distribution of benefits and should be considered when research priorities are set. The inclusion of research spillover affects the net surplus of the home country or home regions where research takes place. This net effect on total surplus can be positive or negative depending on the price elasticities of the supply and demand function and the trade status. An exporting country loses in total surplus (the losses in producer surplus are greater than the gains in consumer surplus) while importing countries gain. The distributional consequences are that research spillover increase the share of consumer surplus at the expense of producer surplus through further depressed market prices. More details on the economics of research spillover are described in ALSTON et al. (1995, p. 219 ff.).

regions which is a rather crude assumption in view of the fussy dynamics of regional trade patterns and price movements.

The disadvantages of scoring models are the advantages of the economic surplus concept, namely, that it is based on a systematic and economically sound analysis of the research environment and the implicit consideration of the market environment to which the researchable commodity is exposed to. Furthermore, economic surplus can be extended to consider along with the efficiency effects a range of distributional effects which opens a large field of macroeconomic analysis and insights into the macro effects of structural policies. It is also open to the inclusion of research-induced quality changes, general-equilibrium feed-back effects, market-distorting policies, and other distortions in incentives such as externalities (see for example, ALSTON et al., 1995, Chapter 4). The economic surplus method has its comparative advantage over other methods when priorities need to be set on international level, e.g., for CGIAR centres or when the country holds a significant share in production and trade of the researchable commodity (large country case). Both situations have in common the need to include the external consequences of research via the effects on market prices and technology spillover to other countries. The advantages over other quantitative methods such as cost benefit analysis are less striking when the distributional consequences are not much of an issue or price spillover effects are assumed to be negligible (e.g., small country case).

There are several limitations to use economic surplus. One is that it requires substantial expenditure for collecting, processing and interpreting economic and technical data. Not only various market information are required but also research specific *k*- factors for each partial market. Considerable simplification is often found with respect to one or a few parameters in order to facilitate application. For example, DAVIS et al. (1987) made simplifying assumptions regarding the potential cost reduction effect (5 per cent research induced unit cost reduction over all commodities) while other parameters are specified more accurately. In the absence of reliable market data, several assumptions are required which may turn the resulting economic gains into highly conjectural information.

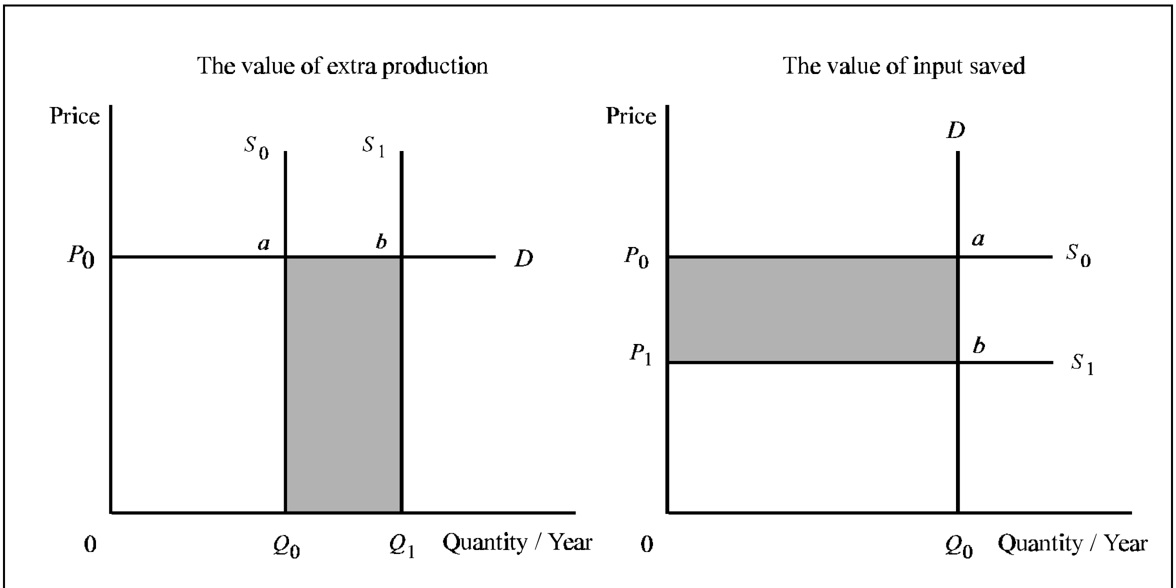
Also, the method requires well-trained analysts to set up the market model in a spreadsheet environment and further, to analyse and communicate the major findings to the stakeholders. Another important deficit is the incompatibility with non-commodity research, such as socio-economic research, basic research, or interdisciplinary research and with the measurement of non-economic and non-monetary objectives such as sustainability or food security. All these research areas and non-economic objectives are all difficult, if not impossible, to couch in a market framework.

2.6.2 Cost-Benefit Analysis

Cost-benefit analysis may be seen as an alternative to economic surplus analysis. In fact it uses the concept of economic surplus except that no accounting is made on the price effects due to the research induced supply shift. Cost-benefit analysis originates from project analysis and evaluation where the effects emanating from a project, e.g., the expansion of production, or increased use of production inputs, are generally perceived as too small to have a significant impact on the price level of a sector or market. The ignorance of price effects leads to the simplification that is: the extra production from research is valued at a single market price that assumes that the supply curve is vertical and shifts against a horizontal demand curve (left-hand diagram in Figure 2-6) or, alternatively, as the value of input saved at the current level of production which implies that a horizontal supply curve is shifting down against a vertical demand curve (right-hand diagram in Figure 2-6).

As with economic surplus, research benefits are measured as changes in consumer or producer surplus and when discounted over time, internal rates of return, net present value and cost-benefit ratio are calculated. The potential advantage of cost-benefit analysis is that no information on price elasticities is required since by assumption demand and supply functions are either vertical or horizontal. Paucity of data and modelling requirement has established cost-benefit analysis as the standard method for calculating the economic gains from research. The disadvantages are that price effects and price spillover effects are ignored as well as the distributional consequences of the economic gains among regions, countries or social groups.

Figure 2-6: Assumptions on markets in cost-benefit analysis



Source: ALSTON et al. (1995, p. 55)

The degree of sophistication found in empirical applications of cost-benefit analyses varies widely. CONTANT and BOTTOMLEY (1988, p. 15) recommend that a minimum standard of accuracy in impact measurement should, at least, include annual research costs, research duration, probability of research success, resulting benefits, rate of adoption, adoption ceiling, and life of the innovation. However, several examples exist where this is not met. Particularly the time dimension of research investment is sometimes neglected and, instead, only some average annual net present values or cost-benefit ratios are calculated (e.g., COLLION and KISSI, 1995; FRANZEL et al., 1995). COLLION and KISSI (1995) proposed a simplified form to be used in priority setting by calculating an annual cost-benefit ratio based on average annual costs and average annual benefits. They did this by replacing technology adoption changes over time by a single adoption estimate. They argued that robust estimates of individual adoption profiles are difficult to obtain, and that an average adoption value better promotes consensus among participants by making calculation easier and more understandable.

Further, the loss in accuracy ignoring time and discounting procedure may count little for the purpose of obtaining a ranking from which to select a set of priority projects (COLLION and KISSI, 1995, p. 41).[8] CONTANT and BOTTOMLEY (1988, p. 14) point out that cost-benefit analysis can be easily adjusted to take into account multiple objectives. For example, foreign exchange earning can be valued above the official exchange rate or alternatively benefits from research on exportable commodities could be weighted higher than benefits occurred for research on food and staple crops mainly consumed at home. Wages can be priced below their real level in order to reflect the advantages of a technology which uses underemployed labour rather than capital. Several examples show such extensions in order to account for non-monetary objectives and non-efficiency objectives by using adjustment factors (or modifiers) in the cost-benefit equation. COLLION and KISSI (1995, p. 29-31) proposed how to complement the cost-benefit formula with a modifier that takes sustainability concern into account.[9] FRANZEL et al. (1995, p. 5, 20) introduced a modifier

[8] The cost of this simplified version are that economic gains may be overestimated (by ignoring lower adoption rates at an early stage of technology dissemination), but more important, it may create internal inconsistencies of the economic gains. Impact of projects with a slow adoption but high final adoption ceiling are overvalued while projects with fast adoption and a low ceiling level are undervalued.

[9] COLLION and KISSI (1995, p. 29) use the following formula in their modified cost-benefit analysis:

Expected project benefit $= \sum \boldsymbol{B_i} = \sum \boldsymbol{V_i} \times \boldsymbol{p_i} \times \boldsymbol{s_i} \times \boldsymbol{a_i} \times \boldsymbol{e_i}$

with V = potential increase in net production value and/or processed output of a given commodity (expressed in monetary values)

p = share of potential attributable to the technology developed by the project (expressed as percentage) to account for the welfare and income of particular groups by adding a percent premium for the generation of income for female-headed households. There is virtually no limitation to the ways of including such non-monetary and non-efficiency objectives in cost-benefit analysis, and many liberties have been taken in doing this. But it should be recognised that considerable subjectivity is added when it comes to weighting such modifiers according to the importance of the objectives and determining the absolute values (the premium size) placed on the effect of a research activity.

2.7 Mathematical Programming[10]

Research projects measured in terms of internal rates of return, net present values and cost-benefit ratios and ranked from highest to lowest are frequently used as a basis for deciding on the set of projects proposed for implementation. The decision consists merely of funding the projects with the highest ranks and moving down the ranking list until all funds are exhausted. Problems may arise because of project indivisibility (i.e., when there is money left but not enough to fund the project next in order), but a satisfactory solution can generally be obtained by a manual check of nearby alternatives. However, when there are multiple constraints, time periods or project funding options, simply allocating funds based upon project ranks is not so appealing (SHUMWAY, 1973).

Mathematical programming (MP) with its various techniques offers an alternative way to such decision problems. The principle underlying a MP model for priority setting is that it selects a set of research activities that maximises an objective function subject to a set of resource and other constraints. Objective function coeficients are the activities' impact estimates. Research activities can thus be single research projects, thrusts or even research programs. Usually MP models are used in priority setting at program level by optimising research program portfolios. According to ALSTON et al. (1995, p. 442) mathematical programming is an optimisation procedure that can be used in the context of priority setting and research allocation to address various different problems such as :

- incorporating multiple objectives and examining the trade-offs between conflicting objectives in a quantitative manner (e.g., the economic efficiency sacrificed to meet a distributional objective);

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s = probability of research success

a = adoption rate of the technology

i = the eco-zones, and

e = adjustment for positive or negative long term indirect effect on production via the environment.

[10] Here, the description of mathematical programming models will be kept very brief. Much more information will be provided in the following chapters of this study (e.g. in chapter 4, 7, 8 and 9) when several mathematical programming approaches will be applied to the KARI dairy research program.

- incorporating a research response function that exhibits constant or diminishing returns to research so that, for a given objective, the mix of a research program that is made up of several research activities can be optimised;
- relating the marginal research benefit to the amount of funds going into research and their deployment, thus addressing the question of optimal allocation and marginal reallocation of research resources;
- examining the implications of changing facilities, human resources, and financial constraints on research; and
- identifying short- and long-run priorities by considering changes in constraints on resources that may be fixed in the short-run but variable in the long-run.

The appropriate procedure for optimising research program portfolios very much depends on the characteristics of the optimisation problem in terms of (a) the objective function to be optimised, (b) the relationship between changes in research activities and the value of the objective function, and (c) the constraints imposed on the solution space. The objective function may be defined in terms of a single objective or may be composed of several research objectives. The objective function values may take discrete and single impact estimates for each project or may take several values each representing different budgeting and project size options. Alternatively, a research response function can be specified that relates research output to a continuous range of research budgets and other inputs and relates research output to its economic impacts. With the latter specification, MP does not only select the optimal research portfolio but also indicates the optimal amount of funds allocated to each research activity.

According to ALSTON et al. (1995, p. 443), mathematical programming models have been formulated for agricultural research resource allocation by RUSSEL (1975), DE WIT (1988), and SCOBIE and JACOBSEN (1992). Apart from these few applications, the attention given to mathematical programming models in priority setting is rather low. The major objections brought against such models are considerable data requirements and methodological complexity which turns MP into a hardly transparent and expensive approach with low potential for participation (JANSSEN, 1994a, p. 5). On the other hand, the advantages of MP can be seen in a rigorous treatment of multiple objectives and the quantification of the possible trade-offs between conflicting objectives. Equally important is the flexible use of various sorts of decision constraints, so that many aspects of the restrictive decision environment facing the research management can be formally incorporated.

2.8 Limitations of Priority Setting Methods in Practical Applications

Care is always needed when a direct comparison of all priority setting methods that have been introduced in the preceding sections must be made with regard to their usefulness in practical situations. As a result of the rather unclear definition of priority setting as a management task and the different disciplinary views in the past, the bundle of priority setting methods is still very large and heterogeneous. However, several methods are likely to become less important or may even disappear. Precedence and congruence are the least suitable methods to deal with the increasing complexity and dynamics of agricultural research systems. With the uptake of completely new research themes and assignment of new development objectives, the historical pattern of resource allocation as a guidance for current and future decisions becomes increasingly obsolete. Priority setting requires more than applying a simple decision rule but must include detailed planning efforts which involves the definition of research activities, and the prospective evaluation of the impact of research on pursued objectives.

Economic surplus and cost-benefit analysis are mostly concerned with efficiency as the predominant research objective. The majority of examples come from commodity research where the costs and benefits from research are estimated and combined with several other criteria. Although both methods differ to some degree in the complexity of measuring the welfare effects they all rest on the same principle which is the direct connotation between agricultural research and economic efficiency gains via technical progress, increase in productivity and final production.

Cost-benefit analysis and the economic surplus approach lie very far on the spectrum of formal economic modelling. Hence, they allow an accurate representation of the economic environment in which research takes place, but are less flexible in integrating apart from the economic dimension of research other research objectives as well as taking into account the institutional framework within which decisions on research are made. Environmental and resource conservation issues are prominent examples for dealing with the multiple objective framework. External costs and future resource scarcity are principally amenable to a market framework, but the calculation of research benefits and the allocation to individual research alternatives become easily intractable.

Another example are the institutional preconditions of agricultural research. If the institutional restrictions e.g., the availability of scientists and facilities, are not sufficiently incorporated into a priority setting model, then the resultant list of research alternatives may not be feasible to implement and other decisions are taken. This points at a general conflict for choosing the right method, which is between the accuracy of ascertaining the impact of research and the flexibility of incorporating different research objectives, research alternatives and criteria of the decision makers. This is not to say that this criticism only applies to economic valuation methods, but these shortcomings are generally true for other methods as well. Another issue is the trade-off between the degree of formalism and comprehensiveness. With the exception of trained economists formal methods such as economic surplus methods are difficult to comprehend and may be perceived as a "black box". If the way results are received is not fully understood decision makers may be reluctant to accept them and turn to intuitive but less rationale decision criteria. At its worst the actual decision making process may be cut off from any formal method.

Another point of controversy is the right degree of planning efforts, this means the efforts spent on evaluation and decision making. Any priority setting effort takes up valuable time for bringing scientists and research managers together. This time could be invested alternatively into the research process. The methodological choice has an direct connotation to these costs since it determines the time needed to introduce the priority setting procedure, the amount of information to be elicited, and the time spent on discussion and final decisions on research plans. Advanced economic valuation methods are inevitably coupled with higher costs than simpler methods. These costs must be balanced against the potential benefits from better decision making. Unfortunately, empirical evidence shows that these benefits have been rather small in the past.

Strategies towards increased efficiency of formal priority setting procedures must be manifold. First, it is necessary to have an adequate understanding of the way actual decisions are made in research institutions. Unfortunately, the driving forces in the decision making process are largely unknown. Priority setting is still too young and institutional and communication sciences have given little attention to research systems as to gain a clear picture of the decision structures. As long as the knowledge base remains so poor, economists and priority setting experts may find it difficult to identify and value the shortcomings of current priority setting procedures and to refine the methodological basis accordingly. Similarly difficult is to comment on the right degree of formalism, simplicity and planning effort. The second strategy is to combine priority setting methods to an integrated approach with each method given a specific task since any method, if applied solely, has its inevitable shortcomings. This implies that priority setting experts would need to examine the complementary effects of methods, e.g., which methods can be linked together, rather to discuss them as competitive instruments. A third strategy is to enhance the methodological basis by exploring the potential of alternative planning and evaluation methods from other disciplines to be used in agricultural research planning.

3 A Case Study: Priority Setting for the National Dairy Research Program

3.1 Introduction

The Kenya Agricultural Research Institute (KARI) is the largest national agricultural research Institute in Sub-Sahara Africa and has the mandate to carry out all national and publicly financed agricultural research in Kenya. KARI has a strong record in setting priorities for its numerous research programs as a means for medium and long-term planning and for attracting funds from national and international donor organisations. KARI has a supportive environment due to the presence of several supra-national institutions concerned with research and development projects in agriculture, ecology, and forestry, e.g., a regional bureau of the Food and Agriculture Organisation of the United Nations (FAO), the International Livestock Research Institute (ILRI), the United Nations Environmental Program (UNEP), or the National Dairy Development Program (NDDP), that provide expertise in many fields of agricultural development. Also, Kenya has a comparatively well developed agricultural data base composed of national agricultural statistics and agricultural surveys from development projects which are valuable sources of information for priority setting.

This chapter reports on the priority setting exercise for the national dairy research program at KARI which has been conducted 1996 in a serious of regional and national workshops. Major stakeholder groups in dairy research were invited to participate, among them farmers' representatives, experts from the national extension service, dairy scientists from KARI and other institutions, and representatives from the ministries. The dairy research program must be seen in the context of KARI's overall effort to set priorities for all its research programs. All previous priority setting efforts have been concerned with crop research programs. The dairy program's priority setting exercise in 1996 was the second attempt to address livestock programs after a first pilot exercise for dairy which took place in 1984. KARI perceives dairy as a key commodity program in its research agenda with considerable resources invested. Dairy production plays also a major role in the agricultural sector and provides significant income for small-scale farmers.

KARI has set up clear guidelines for a program-level priority setting procedure including different working steps, defined research objectives, and the evaluation methodology. These guidelines were translated into an operational framework which has been applied to a series of KARI commodity programs. The priority setting case study described in this chapter draws heavily on the experiences of past priority setting efforts and follows to an large extent the KARI framework whose major characteristics can be summarised as:

- Priority setting builds on the ex-ante assessment of the potential effects of new research activities identified during priority setting while ongoing and past research activities are only evaluated as far as they are useful as background information in the ongoing process. Based on evaluation results research activities are prioritised, i.e., brought into a hierarchical order for implementation, and recommendations are made regarding the allocation of research resources – budgets and scientists – across regions and research centres.

- An economic framework is applied for the assessment of the ex-ante economic gains from research using an economic surplus approach couched in a commodity market model.

- Priority setting recognises the need for incorporating multiple research objectives such as efficiency, equity and sustainability. The measurement of research activities with respect to efficiency is derived from the economic surplus framework. Appropriate indicators and measurement approaches for the equity and sustainability objective depends on the specific circumstances of the commodity program. So, there is no direct guideline of how equity and sustainability should be conceptualised and measured.

However, this priority setting case study discriminates in several respects against past efforts by incorporating a set of new and improved methods emanating from a collaborative project between KARI, ISNAR, and the Humboldt-University of Berlin (HUB) on improved priority setting methods for livestock research. The need for improved methods was especially felt because livestock poses a major challenge for priority setting. Livestock production systems are complex, dynamic, not well explored, and the understanding of how research would affect production systems is rather vague and ambiguous (WAITHAKA et al., 1998, p. 1). The collaborative project came up with four different types of innovative approaches complementing the KARI's priority setting procedure namely: a procedure to define and weigh research objectives for the dairy program; an adoption model to examine the influence of technology characteristics and forecast adoption rates of planned technologies, the integration of a user perspective for the perception of dairy technologies, and a computer based decision support model for priority setting.

This chapter gives first a brief introduction on the importance of the Kenyan dairy production and industry to the national agricultural sector. The next section describes the organisational structure of KARI, its stated priorities, and actual allocation of resources to its different research programs. A brief outline is presented on the established KARI priority setting procedures and the modified procedures developed from the KARI-ISNAR-HUB research project, including the main objectives, research modules and key methodological innovations. The primary attention is given to the description of the analytical framework of the economic surplus approach and the definition of different impact parameters which establishes the basis for methodological extensions developed and introduced in later chapters of this study. The chapter concludes with a summary of the economic evaluation results.

3.2 Dairy Sector Overview

Kenya has a comparatively well developed dairy production and industry compared to other countries in Sub-Sahara Africa. In the early years, after independence, the industry was mostly controlled by large scale farmers, but since then it has changed into a small-scale industry with about 300,000 farmers owning around 3 million dairy animals, which is about 80 per cent of the total dairy herd in Kenya. Dairy activities occupy about 2.8 million hectares in high and medium potential areas in 31 districts of Kenya (KARI, 1994, p. 3; MUTHEE, 1995, p. 1-5). The type of cattle kept include pure breeds, i.e., Frisian, Ayrshire, Guernsey and Jersey, mostly found in large farms, and pure-breed and cross-breeds in small-scale farms. Dairy production in Kenya has experienced significant growth over the last two decades. In 1981, production was estimated at 0.513 billion litres of milk while in 1991 production rose to 1.495 billion litres at an annual average rate of 7.5 per cent. Production is concentrated in the Rift Valley region with 48 per cent of all dairy cattle followed by Central Province with 31 per cent. Still, a significant share of the milk is produced by around 10 million zebu cattle in pastoral systems in semi-arid and arid areas. Pastoral production in 1991 was estimated at around 0.7 million litres of milk, which is normally consumed at home or retailed locally. Indigenous cattle (zebu) have an average milk production of about 300 kg/ lactation period whereas the yield from grade dairy cows usually is in the range of 1,900 to 2,200 kg/lactation.

It should be noted that although the number of dairy cows has been increasing, yields have not increased significantly (MUTHEE, 1995, p. 7). The observed yield increase of 33-44 per cent between 1986-1991 was mostly due to favourable weather conditions rather than to improved milk yield per cow. Large variations exist in the milk yield of grade dairy cows. For example, reported yields in large farms are in excess of 4000/kg/lactation, indicating that a significant potential exists for increasing yield in smallholder areas as well. In Kenya the most important constraints to improved production for smallholders are feed availability, inadequate grazing area, lack of high quality stock, animal diseases, and inadequate artificial insemination (AI) services (MUTHEE, 1995, p. 7). Dairy production systems in Kenya are often classified into three predominant feeding regimes (MUTHEE, 1995, p. 7 ff.): free grazing, semi-zero grazing, and zero-grazing. Free grazing describes extensive production using very small amounts of purchased input or services. It is the predominant system in the arid and semi-arid areas. Many of the producers are pastoralists keeping their herds mainly for milk. Milk yields are generally low and milk is produced mainly for subsistence while any excess milk is marketed informally. Milk production in these pastoral systems is very susceptible to seasonal influence of weather and fodder base but nevertheless constitutes the most important agricultural systems suitable in these low potential areas. In semi-zero grazing systems, cattle are grazed on improved or natural pasture during the day and are kept in shed or "boma" during the night where they are fed forages or crop residues. Significant amounts of feed supplements such as minerals and concentrates are purchased. Disease control measures such as dipping and spraying are commonly used.

In zero-grazing systems cows are confined in stalls during day and night. Zero-grazing is the most intensive system amongst all the three systems described. High levels of input and services are used and the highest milk yields are obtained. This system is predominant in high potential areas with high population density and land scarcity. Dairy production in these areas is facing heavy competition from cropping activities such as tea and coffee, and this has triggered the development of labour and capital intensive zero-grazing technologies. Furthermore, zero-grazing technologies have been promoted with considerable effort in bilateral development projects. For example, the NDDP (National Dairy Development Project) supported by the Dutch government has developed and promoted appropriate zero-grazing technologies in collaboration with the livestock extension service throughout the country for over twenty years (KARI and ILCA, 1990; MINISTRY OF AGRICULTURE LIVESTOCK DEVELOPMENT AND MARKETING, 1992).

During the period 1977-79 to 1986-1988 dairy consumption in Kenya grew at a rate of nearly 8 per cent annually. Also, production increase kept pace with the dynamics of demand indicating a tremendous technical progress and intensification in the dairy sector. Kenya was able to keep import dependency at a negligible rate of 0.4 per cent and has even managed to export surplus dairy products to neighbouring countries except in extremely dry years (STAAL and SHAPIRO, 1994, p. 533). Smallholder dairy in Kenya has long offered higher financial returns than other agricultural activities. Today, milk and milk products rank sixth as farm revenue earners, providing about 16 per cent of total farm income. This establishes for dairy a position as the second most important component of the livestock sector after cattle and calves which contribute 30 per cent and 56 per cent respectively of the gross marketed production in livestock and livestock products (WAITHAKA, 1994, p. 43). Dairy production will continue to have a high potential in generating substantial income for Kenyan dairy farmers in the future (STAAL and SHAPIRO, 1994, p. 533). Until recently, the Kenyan dairy market was strongly influenced by government intervention. SELLEN et al.

(1990) provide an overview of the Kenyan dairy policy. Prices for milk were governed by controls on producer and consumer prices. Furthermore, processing and distribution were dominated by the KCC (Kenya Creamery Co-operative), a large semi-private co-operative which held an official monopoly on processed milk throughout the country. International trade has also been successfully controlled by KCC since it was the only processor able to produce significant exportable surplus. On the import side foreign traders were granted access to the dairy market only with a certification issued by the KCC declaring that KCC is currently unable to supply the products to be imported. The far reaching vertical and horizontal integration of the KCC has strongly impeded the establishment of other milk processors in the market. These processors were additionally disadvantaged though the restriction of their activities in their local regions.

Despite the monopolistic role of KCC dairy farmers have profited – at least have not been worse off – compared to what they would potentially earn in a competitive market because KCC has guaranteed farm gate prices above world market level over many years. Results of a policy analysis study (SELLEN et al., 1990, p. 49 ff.) indicate that zero-grazing farmers especially in milk surplus areas have benefited most from the guaranteed prices; however, in milk deficit areas farmers probably would have received higher prices for their milk in the absence of KCC. Dairy policy has changed dramatically since 1992 with the general liberalisation of the dairy sector after a rapid drop in milk supply and increasing inefficiencies of the KCC. Prices were decontrolled and the official monopoly of the KCC for processing and distribution was lifted. Private processors started to offer increasing competition. Liberalisation also decontrolled informal markets for milk sales in rural areas which was illegal prior to liberalisation in areas where KCC had its operations.

Parallel to liberalisation, the government began a process of re-privatisation and cost-sharing of many services resulting in a tremendous withdrawal of its financial support from veterinary services, vaccination, artificial insemination, dips operations, drugs and input distribution as well as infrastructure. Although liberalisation has brought about more competition and private sector involvement, it has had thus a negative impact on the provision of livestock services and input delivery to farmers. Many services were closed down by the government but were not taken over by the private sector soon after. Since then, lack of agricultural services in full and functioning operations is seen by many dairy experts as the main constraint to improved productivity that could otherwise keep pace with the tremendous population growth (MUTHEE, 1995).

3.3 Institutional Structure, Resources Allocation, and Priority Setting Efforts

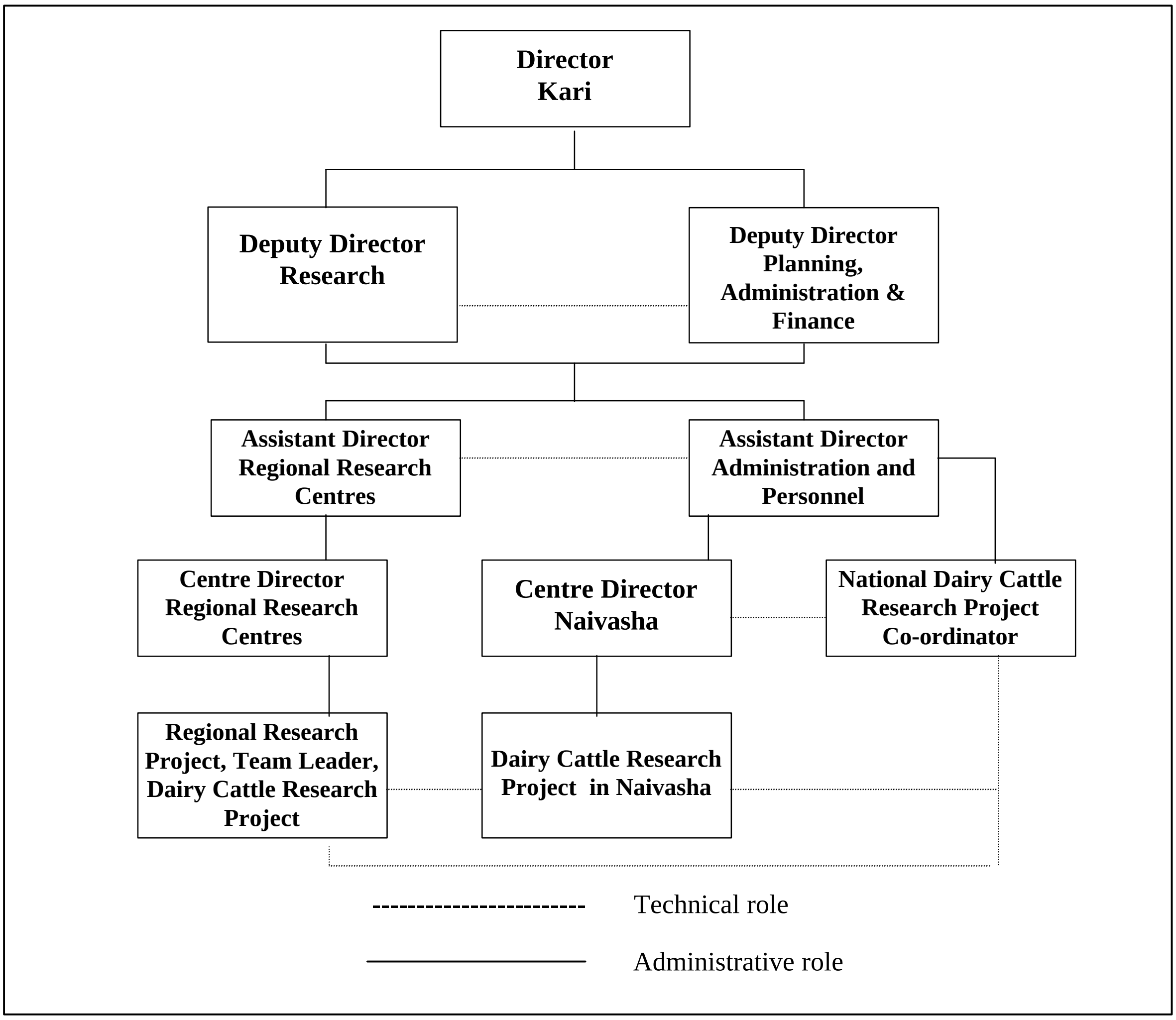
The Kenyan Agricultural Research Institute (KARI) was established by an amendment act of the Kenyan parliament in 1979 and charged with the responsibility of carrying out research in agriculture. KARI conducts research on a total of 86 research programs, 53 commodities and 33 factors. It has two major research departments; livestock and soil, crops and water. KARI's research activities are carried out in 31 regional or national research centres located all over the country and representing different agro-ecological regions and production systems (ABATE and JANSSEN, 1995). National centres are mandated to carry out adaptive and basic research with both national and regional out-looks while Regional Research Centres (RRC) carry out adaptive research. Research co-ordination is done by KARI headquarters located in Nairobi. Currently, dairy cattle research under KARI takes place in 9 Regional and National Research Centres (NRC)[1] which cover about nine different eco-zones. Eight of these are located in the medium and high potential areas with zero grazing and small-scale semi-zero grazing systems as the predominant production types. One regional centre takes care of the research needs in the lower rainfall areas.

In future, KARI will deliberately attempt to include medium and low rainfall areas into its research agenda. It is expected that increasingly more land in the drier parts of the country will be required to produce milk as human population pressure continues to rise in the high rainfall areas (ABATE and JANSSEN, 1995, p. 2). Dairy research in KARI is now undergoing a re-organisation process based on the National Agricultural Research Plan (NARP II) for the period 1994-1995.

Figure 3-1 below depicts the new structure of dairy research under the framework of the National Dairy Cattle Research Program (NDCRP). An important role is played by the National Animal Husbandry Research Centre (NAHRC) at Naivasha which is the co-ordinating centre for dairy and has an advisory function over the dairy regional research centres. Regional Centres are granted autonomy in deciding their research plans based mainly on regional needs. This implies that outcomes of national priority setting exercises are not binding for the regions, but is rather a framework for co-ordinating research between regions (ABATE and JANSSEN, 1995, p. 3).

[1] Regional and National Research Centres occupied with dairy cattle research are the National Animal Husbandry Research Centre (NAHRC) in Naivasha, the Agricultural Research Sub-Centre (ARSC) in Ol Joro Orok, the National Agricultural Research Centre (NARC) in Muguga for the central region; the National Research Centre (NRC) in Kitale, the Regional Research Centre in Kakamega (RRC), the RRC in Kisii in the western region, RRC in Embu, NRC in Katumani in the eastern, and RRC in Mtwapa in the coastal region (ABATE and JANSSEN, 1995, p. 2).

Figure 3-1: Organisation of the National Dairy Cattle Research Program (NDCRP)



Source: ABATE (1995, p. 7)

To gain an impression of the research priorities, the KARI information system (ISNAR, 1995) provides some recent information on the allocation of research resources. As an indication of the relative amount of resources being invested in various commodities, the approximate costs of employing scientists to research on various commodities were taken, since, scientists are by far the largest single cost item. On comparing the relative amount of resources invested in commodities with the national tentative research priorities in the KARI "Blue book" (KARI, 1991), it is apparent that there is a considerable miss-match between declared program priorities and actual resources invested (see Table 3-1).[2] Although national priorities are given to livestock research – the three topmost in the ranking list of the "Bluebook" are the dairy, beef, and sheep & goat programs – the majority of scientists are actually employed in crop research within which 7 commodities are leading in terms of the costs of supporting research scientists.

[2] Nevertheless, the authors of the management system report emphasise that at present only 19 of 31 RRCs are covered. Thus, the figures should be regarded as provisional.

Table 3-1: Stated priorities and resource allocation of KARI research programs

National priorities across commodities (Blue-book 1991)		Resource allocation on 19 Research Centres			
Commodity	Rank	Rank	Commodity	Scientist costs ('000 KSh)	No. of experiments
Dairy	1	1	Maize	2,634	128
Beef	2	2	Sugar cane	1,150	21
Sheep & goats	3	3	Soils	1,148	52
Maize	4	4	Sorghum	1,017	47
Brassicas	5	5	Wheat	919	15
Dry beans	6	6	Cotton	832	9
Irish potato	7	7	Rice	764	25
Sugar cane	8	8	Sweet potato	636	28
Banana	9	9	Cattle	456	24
Poultry	10	10	Beans	453	33
Wheat	11	11	Sunflowers	442	7
Pyrethrum	12	12	Beef cattle	376	5

Source: KARI (1991); ISNAR (1995, p. 19)

Table 3-2: Resource allocation by commodity groups and livestock research

Resource allocation by commodity groups			Resource allocation by livestock targeted research		
Commodity group	Scientist costs KSh	%	Species	Scientist costs KSh	%
Livestock	2,083,198	13.73	Cattle	456,248	21.9
Cereals	5,860,004	38.62	Feed crops	442,922	21.3
Natural resources	1,441,378	9.50	Beef cattle	376,351	18.1
Sugar	1,149,776	7.58	Various unspecified	250,199	12.0
Roots and Tubers	906,092	5.97	Dairy cattle	242,139	11.6
Oilseeds	872,823	5.75	Pastures	174,290	8.4
Fibres	813,949	5.36	Economics	60,916	2.9
Vegetables	734,989	4.84	Sheep & goats	37,545	1.8
Grain legumes	541,321	3.57	Poultry	23,085	1.1
Fruits	510,301	3.36	Bees	19,505	0.9
Industrial crops	n/a		**Total**	**2,083,200**	**100.0**
Spices	34,139	0.22			
Ornamentals	13,710	0.09			
Soils	12,503	0.08			
Pasture	5,039	0.03			
Various	27,134	0.18			
Total	**15,174,670**	**100.00**			

Source: ISNAR (1995, p. 20; 59)

In particular, the dairy cattle research program (DCRP) was ranked first among 53 commodity programs in the 1991 "Blue book" but this is not reflected in the actual resource allocation. Dairy research receives only one fifth of what is allocated to maize research. The figures in Table 3-2 show that even within livestock dairy research is not the top priority commodity unless some experiments grouped under cattle can be assumed to be relevant to dairy research. Other research projects may be related to dairy such as research on napier grass and pastures.[3]

The majority of pasture areas are grazed by large ruminants such as dairy cows. This is even more true of napier grass which is almost planted in Kenya exclusively as green fodder or hay in zero or semi-zero grazing dairy systems. On aggregate, dairy research resources may be considerably higher than indicated but the discrepancy between the stated priority and resource share of dairy is still obvious. According to ISNAR (1995, p. 18) the main reason for the miss-match can be seen, first in the slow pace of program change from the historical pattern of research allocation, and second in the inadvertent influence of factors outside the formal priority setting process, for example, donor influence. International donors often pursue research directions that are not fully in line with current or planned priorities of the national institute. In KARI, foreign donors play a vital role and constitute the major source of funds for research experiments.

In recent years, KARI has made a strong commitment to setting clear and rational agricultural research priorities and to translating these priorities into resource allocation decisions. The institute early recognised the essential need for demonstrating and quantifying the value of its research effort in achieving national agricultural development objectives, particularly in comparison to competing claims for public and donor resources. KARI began in 1991 to set institute-level priorities that looked broadly across all commodity and production-factor research programs. However, the institute's managers felt that institute-level priority setting needed to be supported by more detailed information, e.g., the decisions among research activities within a research program which could be achieved by setting up a program-level priority setting procedure (ISNAR, 1996, p. 6).

KARI set up a priority setting working group composed of internal researchers to develop a formal and consistent priority setting process on program level, and to embed this process in the institutional organisation as a key instrument for research management and planning. The group also made recommendations on a basis framework for the priority setting process, the level at which priorities should be set and the responsibilities at each level (KARI, 1995, p. 1). According to the recommendations, priority setting should generally be

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[3] Scientist costs for napier grass research were reported as around 1,109,000 KSh in 1994/1995 (ISNAR 1995, Figure 2., p. 17).

undertaken at all three levels, namely at the institute, program and project level. KARI expressed the overall objective of setting research priorities at institute level as follows: "*At the institute level clearly reasoned and quantifiable indicators of a prioritised set of potential agricultural research themes increase KARI's ability to set a coherent and stable research agenda with the government and donor community*" (KARI, 1995, p. 3). At the institute level, priority setting should be undertaken every five to ten years and should provide guidance for the division of resources between the Headquarters, NRCs and RRCs.

At the program level the objective was formulated as: "*Program-level priority setting should focus on evaluating the potential contribution of major program research themes to national development objectives*". Program level priority setting effort should occur more frequently than institute level effort and should be carried out every three to five years. KARI emphasises in its recommendations the need for a coherent priority setting methodology and process across commodities and factors to make results comparable and to allow a synthesis of program-level information for the institute-wide priority setting process.

At project level, the working group recommends that the technical committee of the RRC and NRCs should be the appropriate forum to decide which projects to fund within prioritised research themes from program level. This means, it is not recommended to quantify and rank potential benefits of every potential research project in a formal priority setting exercise (KARI, 1995, p. 8).

Table 3-3: A five-step priority setting procedure for commodity programs

- compile an information base on the commodity;
- identify research program target zones;
- assess the potential for technology generation and adoption for major research themes;
- estimate (ex ante) research-induced benefits using the economic surplus concept;
- present results to the program stakeholder group.

Source: MILLS (1995); ISNAR (1996, p. 7)

Assisted by experts from ISNAR, the priority setting working group was heading the development of a general framework for a consistent process and outlined recommendations on the different steps and sequences as well as on the methodology to be applied (see Table

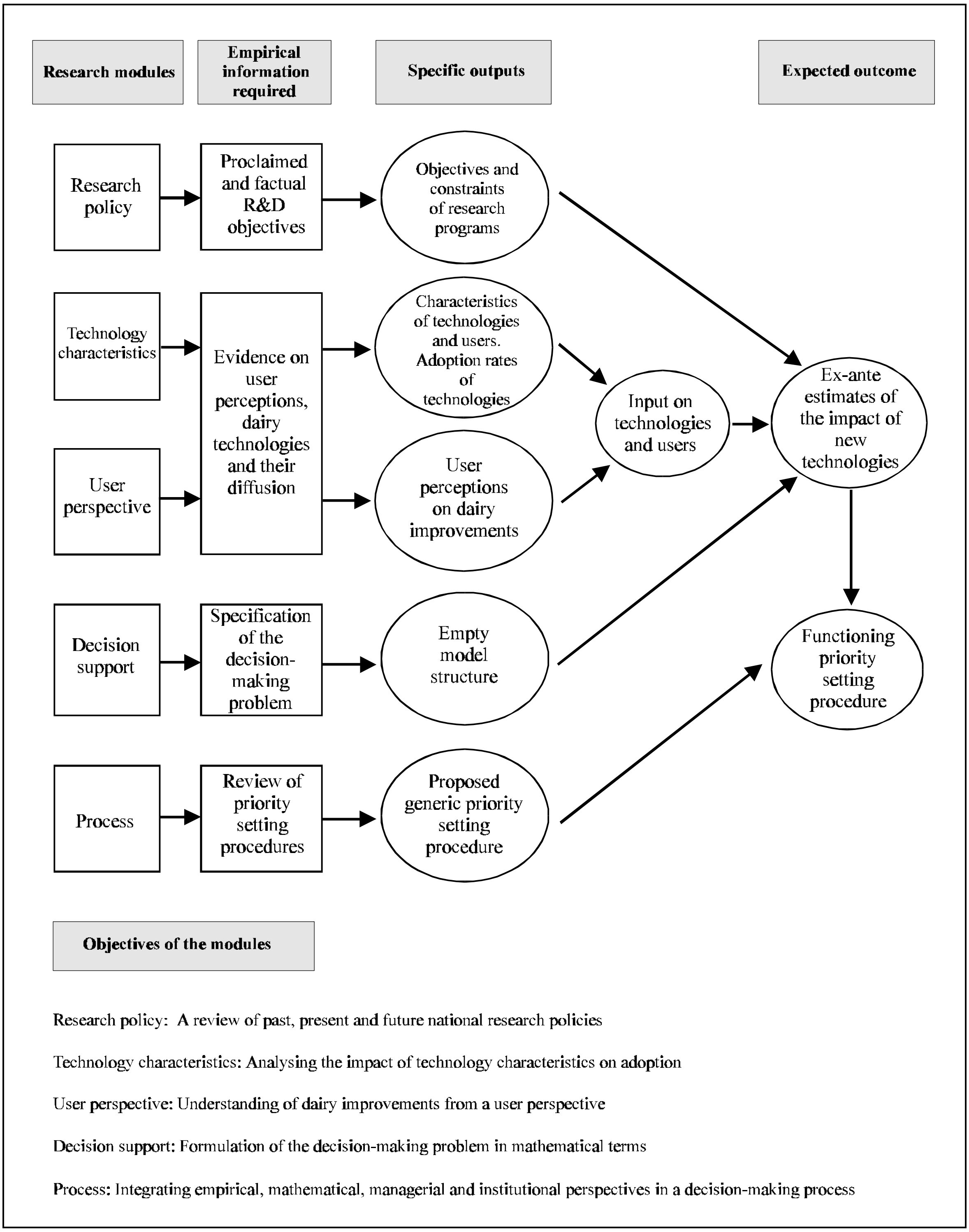
3-3). The existence of a consistent priority setting process should facilitate fast accumulation of expertise in setting priorities for the different commodity and factor-based programs, and to make program results comparable and operational for institute-level priority setting. Based on these recommendations and assisted by ISNAR, the KARI's socio-economics division conducted four pilot priority setting exercises – for the maize program (MILLS et al., 1995), the wheat program (MILLS and KARANYA, 1997), and the sorghum and millet programs – to test and refine the method. The horticulture and oilseed programs are still in the process of planning program priority setting methods although preliminary results are already available for Snap Bean and Brassica research (KAMAU and MILLS, 1996). Only minor progress has been made in prioritising factor based research such as soil science or natural resource management research due to the complexity inherent in impact assessment (MILLS and KARANYA, 1994). No priority setting for factor based research has yet been successfully completed.

As with horticulture, livestock program priority setting lags behind the achievements already made by crop programs. This probably reflects KARI's aim of gaining prior experience in priority setting with crop programs before moving to the more complex livestock sector. KARI is currently establishing an institutional framework, i.e., a data base for livestock systems in Kenya as well as a classification of livestock target zones that should facilitate priority setting. In 1991, KARI has made a first attempt for a livestock program with a priority setting workshop for the National Dairy Cattle Research Program (KARI, 1992). Because it was conducted prior to the working group's guidelines, the exercise exhibits significant differences from the KARI procedures as outlined in Table 3-3. Furthermore, a common need was felt for improved methodologies that are capable of dealing with the complexity inherent in livestock systems.

3.4 A Modified Priority Setting Procedure for the Dairy Research Program

In February/March 1996, KARI conducted a priority setting exercise for the national dairy research program. With this exercise, it was possible to apply some new and innovative approaches developed from the collaborative research project to improve priority setting for livestock research. The collaborating institutions were the International Service for National Agricultural Research (ISNAR), the Kenya Agricultural Research Institute (KARI), and the Humboldt-University of Berlin (HUB). The overall objective of the project was to improve current priority setting methods at the program level for livestock research by developing better ways of estimating adoption rates as an essential criterion for decision making (KARI et al., 1994). This was to be achieved through five major research modules as outlined in Figure 3-2. These modules constitute individual research studies whose responsibility was shared between the collaborative project partners.

Figure 3-2: The KARI/ ISNAR/HUB research project structure



Source: WAITHAKA et al. (1998, p. 11)

The *research policy module* comprises a study on research objectives which recognises the importance of emphasising the right objectives as the staring point for research planning and to guide priority setting processes. The aim of the study was to identify the most important agricultural policy objectives for the dairy sector, and then, to derive interpretable and reconcilable intermediate research objectives for the dairy research program in order to turn broad sector policy objectives into operational ones for priority setting.

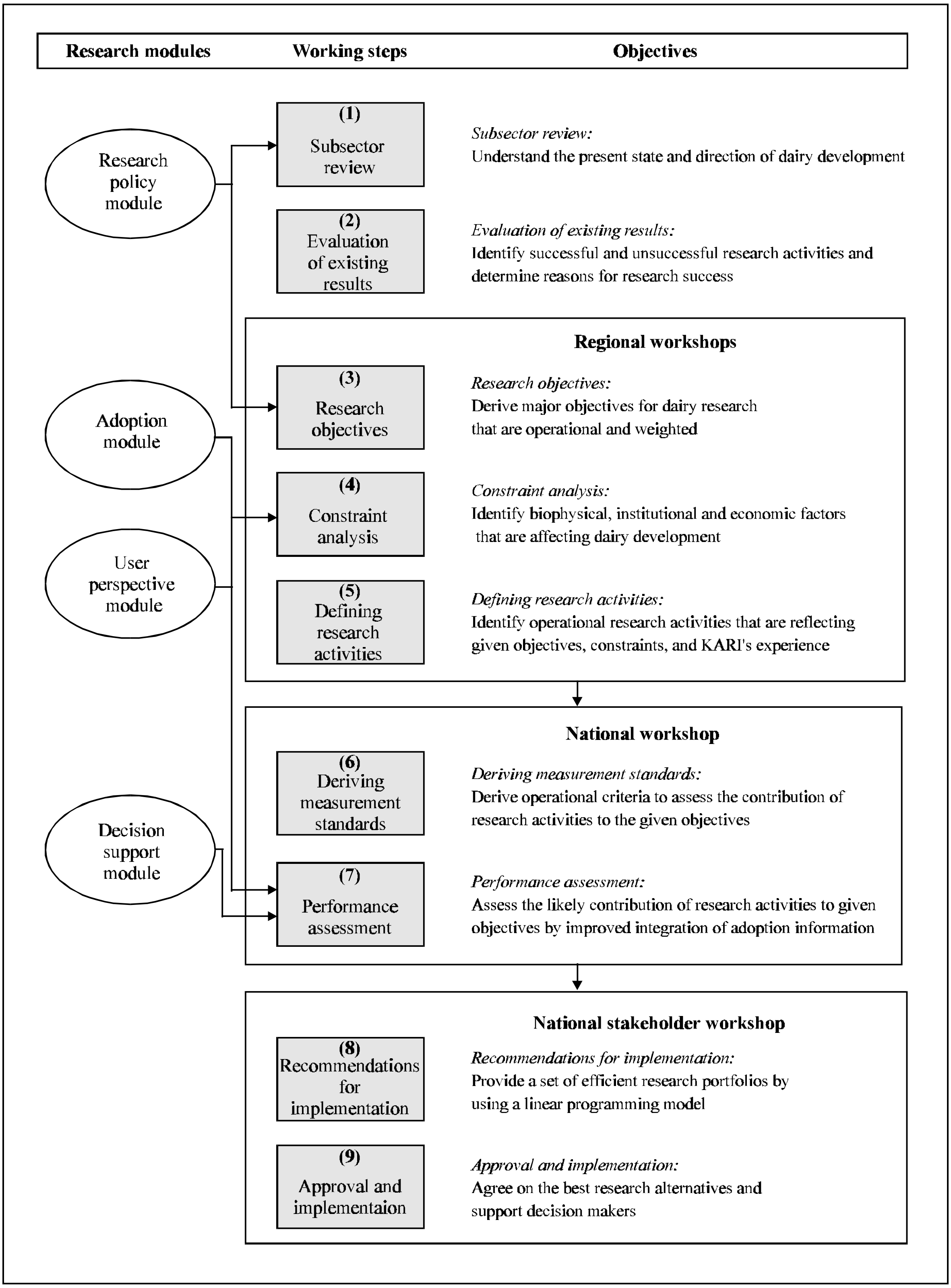
The study to assess the impact of technology characteristic on adoption (*adoption module*) was aimed at filling an apparent gap in the knowledge of adoption processes in livestock systems. Based on a field study on adoption of zero-grazing technologies in dairy, major technology characteristics were identified and analysed with regard to their impact on the speed and ceiling of adoption. The intention of the adoption model in priority setting was to predict the adoption process over time for generated technologies as the outcome of proposed research projects.

The study on user perspective (*user perspective diffusion module*) recognises that market forces have little influence in the short run on priorities and products of public research. There is no guarantee that research will be oriented to the users. Farmers being the final clients should have their say in research planning and what research should offer them. Their interests and priorities rather those of researchers should play a leading role in defining the research agenda. The user perspective study explores ways of improving the understanding of the user perspectives, as well as means to integrate users more strongly in decision making for research program planning.

A decision support model (*decision support module*) was developed to support two stages in priority setting which is the calculation of the ex-ante impact estimates based on an economic surplus approach and the selection of prioritised research projects within a multiple objective framework. The model was designed as a computer based spreadsheet application and placed special emphasis on open model structure and interactive use. The aim of the *process module* is to develop the procedural framework to make the different research module compatible and combine them to a consistent priority setting procedure. The procedure is outlined in Figure 3-3 and consists of 9 major working steps.

Comparing the research project’s priority setting approach with the KARI approach reveals some major differences. First, research activities are not specified in terms of broad thrusts, e.g., animal health or feeding, but are defined as individual projects with a clear specification of the kind of technology or technology packages to be generated. It was hoped that, based on detailed projects rather than on broad thrusts, it would be possible to accelerate the elicitation process of the estimates of technology generation, adoption, yield increase, research costs and other parameters and to generate more reliable information.

Figure 3-3: Stepwise priority setting procedure for the dairy research program



Source: Modified, after KARI et al. (1996, Annex 2)

Second, the process of technology adoption is assessed indirectly through perceived technology characterises such as profitability, complexity, and initial costs. Those estimates are then fed into an adoption model within which the adoption profile of a technology over time is anticipated.

3.5 Dairy Research Objectives and Objective Weights

Like many other commodity research programs in Kenya, dairy research must contribute to multiple development objectives in the country. Research planners and policy makers translate these macro-policy (or development) objectives into research objectives, priorities and strategies. Several dairy policy studies and sub-sector reviews have given information on these objectives and their relative importance for agricultural development.[4] Prior to the dairy workshop in 1996, a dairy policy study had been carried out by HITZEL (1997) with an empirical analysis of the national development and research objectives including a comparison of their relative importance and a validation of the objectives through dairy research stakeholders in Kenya.

Development objectives were derived from policy documents, stakeholder interviews and factual objectives as observed in the implementation (HITZEL, 1997, p. 3) while dairy research objectives were drawn from the stated development objectives and the recommendation made by the KARI priority setting working committee (KARI, 1995) about research objectives that should be used in program level priority setting. An Analytic Hierarchy Process (AHP) was employed as interrogation technique to validate the objective weights by the workshop participants.

Table 3-4 outlines the macro-policy and dairy research objectives and their attached weights indicating their relative importance. The stakeholders weighted efficiency highest followed by equity (defined on a regional basis) and sustainability (defined as loss of soil and soil quality in fodder production). The KARI priority setting committee has made recommendations on how these objectives can be made quantifiable and amenable to the economic surplus concept. Efficiency as the basis of priority setting efforts should be based on consumer and producer surplus. The measurement of equity should be based on the distribution of efficiency benefits either regionally or by target groups, while, for sustainability no methods and information for measuring the impact of research are available yet (KARI, 1995, p. 13-14). It should be noted that, as with the difficulties of the committee to approach the measurement of sustainability, participants of the dairy research workshop were unable to assess the sustainability effects of the dairy research projects. The sustainability effect was based on the proposition that several dairy projects, mainly from

[4] Many studies on the Kenyan dairy sector and dairy policies are cited in HITZEL (1997).

the feed resource thrust, may have a long-term positive effect on soil fertility which eventually could be expressed in monetary terms by calculating the value added from the yield increase of representative crops planted on these soils.

Table 3-4: Weighted macro-policy and research objectives for dairy research

Rank	Macro-policy objectives	Average pairwise comparison weights
1	Generation of employment and income	0.34
2	Food security	0.31
3	Proper management and conservation of natural resources	0.15
4	International competitiveness	0.13
5	Reduction of public sector involvement	0.07
	Total	1.00
Rank	**Dairy research objectives**	**Average pairwise comparison weights**
1	Economic efficiency (increasing milk production)	0.50
2	Equity (regional equity)	0.23
3	Sustainability (reducing soil loss)	0.27
	Total	1.00

Source: HITZEL (1997, p. 13; 15).

3.6 Agro-Ecological Zonation and Regional Markets

Kenya has a tremendous diversity of ecological environments and production systems. In an attempt to account for this diversity, a stratification of the country’s dairy regions was undertaken to identify and demarcate those areas likely to have a fairly homogeneous biophysical impact on dairy technologies. From the regional workshop, rainfall and temperature were identified as the key environmental determinants. Based on these determinants, eight major dairy target (agro-ecological) zones were developed (Table 3-5) from a Geographic Information System (GIS). After discussion with the workshop participants it was agreed that two zones should be dropped, namely the low rainfall 2 zone because of an evapotranspiration level too high for fodder production, and the high rainfall 3 zone because of the high *East Coast Fever* incidence. The final zonation consists of six target zones (Table 3-5, and Figure 3-4), and was viewed by the experts as sufficiently accurate to represent the country’s environmental diversity with respect to dairy farming.

Table 3-5: Agro-ecological zonation for the national dairy program

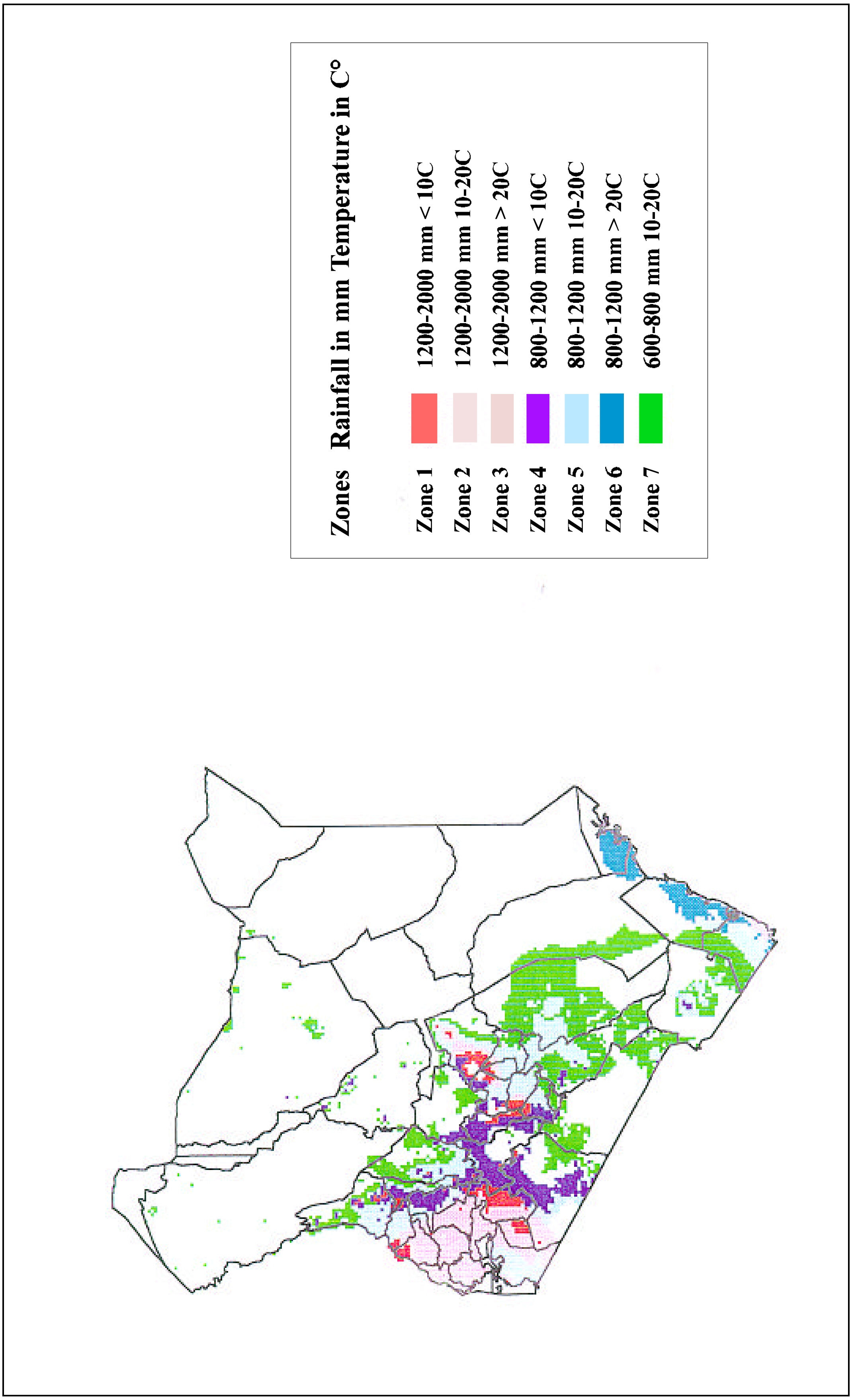
Zone No.	Abr.	Zone name	Rainfall (mm)	Minimum Temperature ^{O} C
1	HR 1	High rainfall 1	1200-2000	<10
2	HR 2	High rainfall 2	1200-2000	10-20
3	MR 1	Medium rainfall 1	800-1200	<10
4	MR 2	Medium rainfall 2	800.1200	10-20
5	MR 3	Medium rainfall 3	800-1200	>20
6	LR 1	Low rainfall 1	600.800	>20
7 (dropped)	*HR 3*	*High rainfall 3*	*1200-2000*	*10-20*
8 (dropped)	*LR 2*	*Low rainfall 2*	*600-800*	*>20*

Source: KARI (1996, p. 3)

In a next step, data from official district statistics – area, population, milk production and consumption, and prices – were taken and extrapolated to the target zones. Two assumptions were made for calculating dairy production. First, that there is no significant dairy production in those areas not covered by the zonation – aggregated zonal production is therefore almost identical with the national figures – and second, that milk produced from zebu cattle mostly in the medium and low rainfall zones be dropped because zebu cattle is not targeted by KARI’s dairy research. Production estimates were calculated from district level data and the agricultural "data compendium" from 1990 (GITU, 1992). Because dairy consumption is not reported for districts, average national figures of dairy consumption were calculated (90 kg per capita and year) and assumed to be the same across all dairy zones. Zonal milk prices were derived from retail and farm gate prices on district level and weighted by the proportion of the districts on total production in a region. Regional price differences are held constant and are assumed to represent all transaction costs from shipping surplus quantities to deficit regions.

Agro-ecological zones were used to define regional dairy markets as a basis for a regional trade model to calculate the economic gains for dairy research activities. Although AEZs are generally specified by bio-physical criteria and not by regional trade pattern, this simplification was justified by a lack of information regarding the stratification of rural markets in Kenya and the trade flows between these markets. A more accurate method for the identification of regional market is "spatial referencing". An application of this method for a KARI priority setting exercise can be found in MILLS et al. (1995). In addition to the dairy production zones in rural areas, dairy consumption of the major cities Nairobi and

Figure 3-4: Map of the agro-ecological zones for dairy research in Kenya



Mombasa, as well as other large provincial cities were assessed and aggregated to a single consumption market called "Nairobi, Mombasa and other urban areas" in order to balance national consumption with national production. As with the production zones, the quantity consumed was derived from population data and consumption per head. The price level was calculated from the dairy prices in Nairobi and Mombasa (dairy prices in other cities were not accessible), and weighted by the proportion of the cities on consumption.

Table 3-6 presents the geographic and economic information for the six agro-ecological zones representing the regional markets in rural areas and for the major cities and other urban areas. As can be studied in Table 3-6, prices in surplus regions are slightly higher than in the deficit regions including the major cities and urban regions. This may be a sign of considerable market imperfection in the Kenyan dairy market caused by high transportation costs, poor infrastructure, large travel distances and expensive logistic systems that makes the trade of milk and milk products in rural areas very expensive. On the contrary, infrastructure and market access is much better for the major consumption centres.

Table 3-6: Geographic and market information for regional dairy markets

Agro-ecological zones (AEZs)		Total area	Population	Production		Consumption *	Net surplus	Average milk price **
		(sq.km)		(' 000 kg)	%	(' 000 kg)	(' 000 kg)	KSh / kg
HR 1	High rainfall 1	7,036.08	1,569,006	180,968	9.19	141,508	39,461	13.51
HR 2	High rainfall 2	25,582.94	6,581,772	523,740	26.60	593,606	-69,866	14.62
MR 1	Mid rainfall 1	19,842.98	2375,162	404,393	20.54	214,214	190,179	13.64
MR 2	Mid rainfall 2	34,902.66	4762,955	466,751	23.70	429,568	37,183	14.23
MR 3	Mid rainfall 3	11,387.34	617,197	26,358	1.34	55,665	-29,306	20.13
LR 1	Low rainfall 1	63,201.28	4,066,788	365,982	18.59	366,781	-799	14.79
Nairobi, Mombasa and other urban areas			1,849,957	0	0.00	166,862	-166,862	13***
	Total	**162,964.74**	**21,822,837**	**1,969,204**	**100**	**1,968,204**	**0**	

All data are for 1990; compiled from various district agricultural reports and from the agricultural data compendium (GITU, 1992);

* Milk consumption figures are based on 90 kg per year and per capita;

** Derived from district milk prices. Milk prices are calculated as the average of the district prices and weighted by the production share of the district in the agro-ecological zones.

*** Derived from milk prices in Nairobi and Mombasa, and weighted by the consumption share.

Source: KARI (1996, p. 4)

It can be seen that zones 2 to 4 are the most important zones in terms of production. The highest production intensities (production/area) are found in the HR 2 and MR 1 zones in which production systems are heavily based on dairy. Dairy production in HR 1 and MR 2 are less intensive due to low temperature and high competition of dairy with tea production (HR 1) and the high evapotranspiration for fodder production in MR 2. Due to lack of information regarding regional trade and demarcation of market centres, agro-ecological zonation was taken as an approximate basis for classifying regional markets for the regional trade model and the calculation of the economic welfare effects.

3.7 Potential for Generation and Adoption of Dairy Technologies

The benefits from research investment in dairy can be measured by valuing the various products emanating from success completion of research activities. If implemented, these research activities may lead to the development of new technologies which, if adopted by farmers, result in improved yield performance or reduced production costs. The factors that are taken into account to assess the potential for generating improved yield performance or reduced production costs are:

- potential yield increase of a technology;
- probability of research success;
- adoption of the technology over time; and
- research and development lags.

Since research investments under consideration are new dairy projects no empirical information on these parameters are available. Instead, dairy experts participating in the national priority setting workshop were asked to give their subjective opinion on each of the parameters. The interrogation of the participants was organised in group work. Groups were structured around the four major research thrusts of the dairy research program, namely feed resources and utilisation, animal health, breeding and genetic improvement, and socio-economics. Each group had to complete the assessment of the parameters for dairy projects of one research thrust. Information concerning net yield increase, probability of research success and technology adoption should be given by research project type for individual agro-ecological zones. Information on research and development lags should be given only by project type.

The elicitation process incorporated some measures to control for the biases inherent in these subjective estimates by grouping dairy experts together from similar disciplines. This way, it was hoped to strengthen expertise in discussing complex and technical questions of the dairy production system in order to arrive at reliable parameter estimates. Furthermore, elicitation results were reviewed in a follow-up meeting to check for possible inconsistencies, especially between group results. Another step to securing reliable estimates was the use of a sound conceptual framework for elicitation of technology generation and adoption based on the approach outlined in ALSTON et al. (1995, p. 351 ff.), and MILLS and KARANYA (1997, p. 67 ff.).

3.7.1 Elicitation of Yield Increase and Research Success

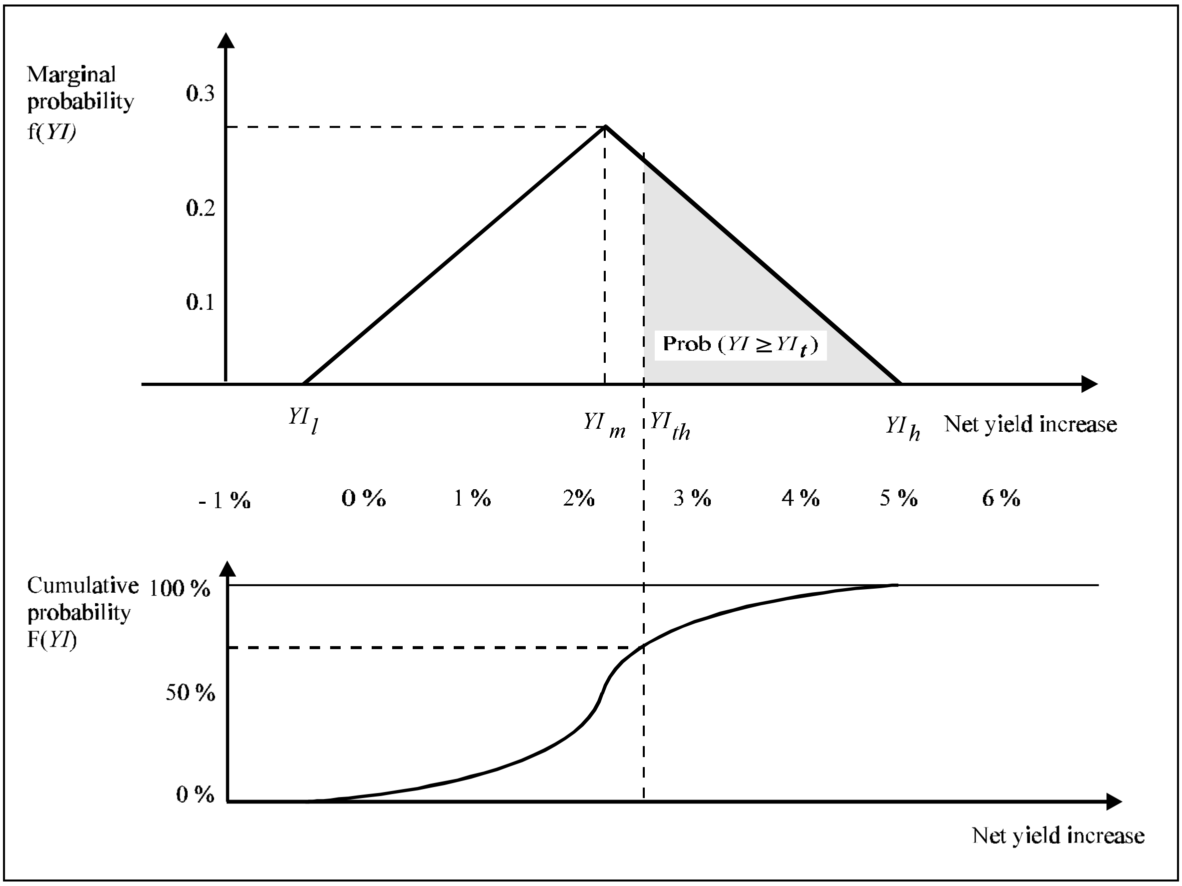
Technology generation, by the nature of the research process, is uncertain and best represented as a distribution of possible outcomes. For commodities, outcomes are most commonly conceptualised in terms of yield increase or cost reduction. The working groups specified research outcomes in terms of yield increase. However, such yield increases need to take into account additional input costs, which lower the effective value of yield gains. Information was gathered on additional input costs which was then subtracted from yield increase by conversion into equivalent negative yield increase to arrive at net yield increase.

Yield increase was specified in terms of minimum (YI_l), most likely (YI_m), and maximum possible outcomes (YI_h). These outcomes were assumed to form a triangular probability distribution such as one as outlined in Figure 3-5. The triangular probability distribution has no theoretical basis but derives its statistical properties from its geometry. If no empirical evidence suggests other distributional forms, the triangular distribution has some major advantages in describing the stochastic nature of a parameter. It is considerably flexible with regard to shape (symmetric and non-symmetric), has intuitively interpretable parameters (the minimum, most likely, and maximum value), and values are defined only for a realistic interval. Also, distribution parameters, such as the mean and variance, can be described in simple mathematical terms. The triangular distribution has therefore achieved a great deal of popularity among simulation modellers and risk analysts (VOSE, 1996, p. 89). The triangular distribution was then corrected for additional input costs by replacing all yield increase values through net yield increase values, which causes, if additional input costs are assumed, a "shift" to the left.

A more rigorous definition of what is commonly referred to as "the probability of research success" was also incorporated into the elicitation process in order to properly account for research outcomes with no possibility for dissemination. Farmers will only adopt technologies if net yield increases are significantly greater than zero. A threshold level for adoption can be defined as the subjective level of net yield increase below which technologies will not successfully pass through the on-farm testing and evaluation phase of the research cycle and will not be released for dissemination. Based on this dissemination threshold, which is graphically sketched in Figure 3-5 as YI_{th}, it is possible to calculate two parameters derived from the triangular distribution function: (1) the probability of exceeding the dissemination threshold YI_{th} for the technology to be released (also denoted as the probability of research success); and (2) the expected net yield increase conditional on the dissemination threshold being exceeded.[5] The formulas for the two parameters can be stated as:

- Probability of research success (RS) = Prob. ($YI \geq YI_{th}$)
- Expected net yield increase YI_e= E($YI \mid YI \geq YI_{th}$)

Figure 3-5: Modelling the probability of research success and expected net yield increase from a triangular probability distribution



Source: Modified, after MILLS and KARANYA (1997, p. 69)

Figure 3-5 depicts the concept of the threshold value and the calculation of the two parameters in graphical form. Let YI be the net yield gain of an innovation. The minimum

[5] MILLS and KARANJA (1997, p. 68) remark that in the standard framework for the ex-ante calculation for research benefits, probability of research success is multiplied by the expected net yield gains across the full distribution of possible outcomes. This practise erroneously includes outcomes with no possibility of occurrence on farmers' fields in the calculation of expected net yield gains.

possible net yield increase is YI_l, the most probable is YI_m, and maximum net yield increase is YI_h. The minimum net yield increase necessary for this innovation to be released for dissemination and adopted by farmers is the threshold value YI_{th} (around 2.7 per cent net yield increase in this example). For every YI there is a corresponding probability $f\,(YI)$ which is assumed to follow a triangular distribution. The probability of achieving YI_{th}, Prob. ($YI \geq YI_{th}$), is given by the cumulative density function below. In this example, the probability of a net yield gain above YI_{th} is approximately 25 per cent. The expected net yield gains is the expect value of YI_e, conditional on YI_{th} being achieved: $YI_e = E(YI \mid YI \geq YI_{th})$.

Two major drawbacks of this threshold concept are that first; the "conditional expectation" of the yield increase parameter, and second; the abrupt cutting edge between success and failure may not be fully appreciated by the people providing the information. Moreover, as ALSTON et al. (1996, p. 353) argue, the meaning of research success may not be clear either. They propose the use of an unconditional yield increase indicator by integrating the distribution of possible yield estimates over the entire value range.[6] This would also facilitate measurement since the calculation of the conditional net yield increase poses some algebraic difficulties.

One could even argue that research success could be totally omitted assuming that there is always some final result at the end of a research effort whose effects are sufficiently covered by assessing potential yield increase and adoption rate. Unless research success is defined meaningfully it is difficult to asses the validity of the information elicited from scientists and derive reliable impact estimates, thus, the meaning of research success needs some further elaboration.

Workshop participants of the priority setting exercise did not always succeed in translating technology effects straight into reliable estimates of net yield increase – for dairy it is the percentage milk increase per cow – since, as with other livestock systems, dairy technologies have several outputs. Dairy production produces various kinds of marketable output such as milk, meat and calves for sale, and intermediate products that all contribute to dairy profitability. Dairy technology may also be targeted at different levels of the dairy herd: on calves, on heifer or lactating cows, and at different subsystems like feed production, etc. To overcome these difficulties experts cautiously stated the outcome of the dairy projects either in terms of percentage increase in milk yield or, alternatively, in terms

[6] The use of the expected net yield increase conditional on exceeding YI_{th} in combination with research success reveals a quite strange phenomenon, that is, changes in the threshold value do not significantly alter the product of research success and yield increase as they enter the formula for calculating the *S*-shift value. Increasing the threshold value reduces the research success but this is largely offset by higher expected net yield increase.

of percentage reduction in variable costs. The following recommendations were made:

- Percentage milk increase should be used whenever possible, especially for project types whose technology directly affects health and nutrition of the milk producing cows. For simplicity, milk increase should first be assessed as gross milk increase, and in a second step, additional input costs should be included, converted into negative yield gains, and finally subtracted from the gross yield gains to derive net milk increase effects given constant costs.

- For dairy project types that do not directly concern lactating cows but heifer or calves (e.g., improved calf feeding or vaccination for calves and heifer), technology effects should generally be approached from the cost reduction side by accounting for the effects on variable costs. Changes in fixed costs were assumed to be small and hard to transform to an annual basis. As with the first alternative, percentage cost reduction is then converted into comparable percentage net yield increase.

- Whenever possible other marketable products such as meat should be accounted for, e.g., when dairy projects have a pronounced effect on live weights and thus on the market price of calves, heifer and cows for sale. Price differences should then serve as an indicator of the increased profitability and translated into gains in milk yield which should be added to the initial yield increase figures. For simplicity, intermediate products were largely ignored.

Some precaution was necessary to avoid possible overstatement of the gains in milk yield or reduction in variable costs. Several projects address seasonal production constraints or bring about improvements only within specific productive stages of the animals. Because yield changes are calculated on an annual basis, seasonal effects (e.g., improved fodder provision during the dry season) needed to be scaled down according to the number of months to arrive at annual estimates.

Table 3-7 highlights the elicitation results for net yield increase, probability of research success, and conditional net yield increase based on the concept of the dissemination threshold for a selected research project. [7]

Table 3-7: Elicitation results for net yield increase and research success of a dairy

[7] Results for the remaining dairy research projects can be found in Appendix *A*.

research project

Project No. 3	Development and utilisation of diets for heifers and cows using locally available feedstuffs						
	Net yield increase estimates						
Agro-ecological zone	Minimum value	Most likely value	Highest value	Dissemination Threshold	Increase in production costs	Probability of research success (%)	Expected net yield increase (%)
HR 1	6.25	25	45	12.5		94.62	26.27
HR 2	16.5	33	50	25		86.92	34.83
MR 1	12.5 (5)	20 (12.5)	30 (22.5)	15	15	32.14	17.2
MR 2	15 (7.5)	33.5 (26)	40 (32.5)	15	15	87.84	23.32
MR 3	12.5 (5)	30 (22.5)	42.5 (35)	12.75	15	88.56	22.21
LR 1	Not applicable						

Numbers in brackets indicate corrected yield increase estimates after a follow-up review

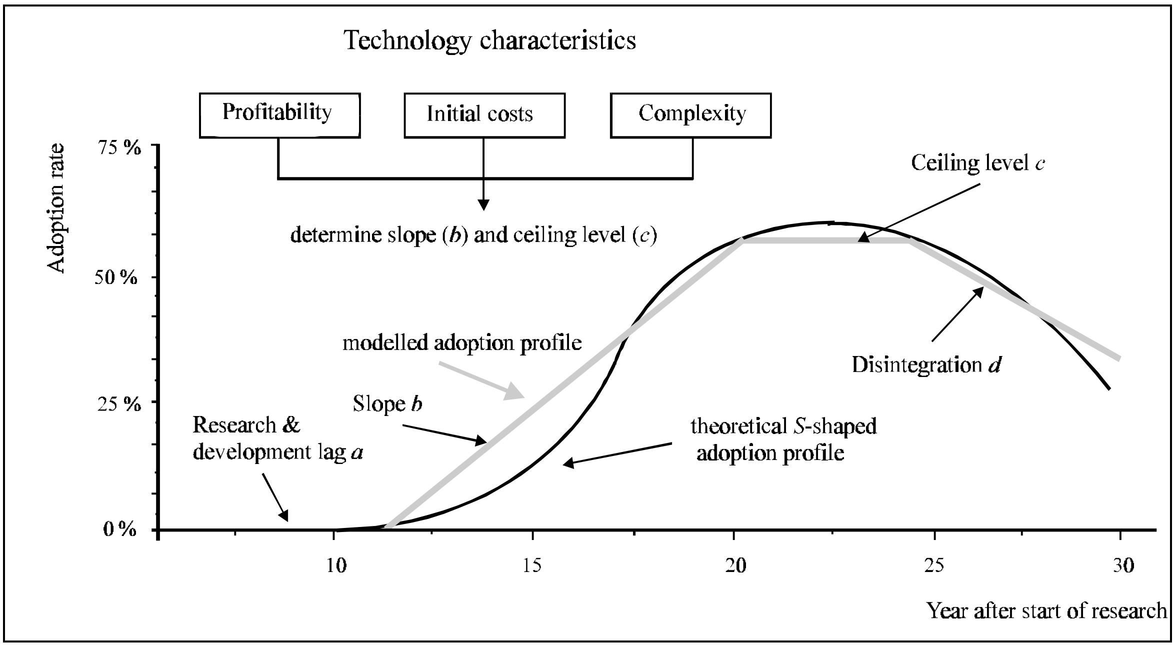
3.7.2 Technology Adoption

Research impact will also depend on the rate and extend of adoption of technologies. Thus, it is essential to include an assessment of the likely adoption pattern. As outlined in Figure 3-6, adoption is a dynamic process that starts some time after the research outcome is released for take up. Some time will invariably pass before first adoption takes place, while in the second phase adoption steadily increases and reaches a peak at the ceiling level of adoption. At the end of a technology cycle, disintegration of the technology starts with the upcoming of a second-generation technology. For modelling reasons, the adoption curve, which is normally sketched as a smooth S-shaped profile, has been partitioned into linear segments. Several basic characteristics of this profile should be noted. These are labelled in Figure 3-6 as:

- the research and development lag (*a*), ending with the release of the new technology;
- the initially increasing adoption rate (*b*) as a growing number of farmers in the dairy regions become exposed to the technology;
- the adoption plateau (*c*), also called ceiling level of adoption, where most farmers have been exposed to the technology and have decided whether or not to adopt; and
- the declining adoption rate (d) as the technology becomes obsolete.

→

Figure 3-6: Modelling the profile of technology adoption



If combined, these elements form the complete profile of technology adoption and determine the speed and frequency with which research results are translated onto farmer's fields. Adoption makes the effects of research very different because technologies tend to have different adoption paths in different locations. The adoption process may be understood as a modifier that translates potential research effects into actual effects over time, indicating each year a different rate of adoption.

Unlike the procedure used for elicitation of technology generation, the assessment of adoption profiles was not done in a direct way by asking experts on the different adoption parameters such as those outlined in Figure 3-6, but an adoption model was used that made the prediction of technology adoption dependent technology characteristics (BATZ and PETERS, 1998, p. 43). The preposition of the adoption model is a functional relationship between perceived technology characteristics by farmer's decision for adoption. For dairy production in Kenya, three major technology characteristics were identified: profitability, initial investment costs, and complexity. Dairy experts were asked to assess adoption by assigning subjective scores on these technology characteristics for each research project and agro-ecological zone. Finally, the scores were fed into the adoption model to determine the speed *b*, the ceiling level of adoption *c*, and adoption level at the end of the planning horizon (30 years) as the basis for calculating annual adoption rates. Table 3-8 highlights adoption results for a selected dairy research project derived from assigning subjective scores on technology characteristics.

Table 3-8: Technology characteristics and derived adoption profile of a dairy research project

Project No. 3	Development and utilisation of diets for heifers and cows using locally available feedstuffs						
	Research and development lag			Technology characteristics			
Agro-ecological zone	Research lag (1)	Time to dissemination (2)	Begin of dissemination (1+2)	Profitability	Initial costs	Complexity	Adoption level after 30 years
	Years	Years	Years	Scores	Scores	Scores	%
HR 1	4	1	5	7	2	12	55.06
HR 2	4	1	5	7	3	12	54.55
MR 1	4	1	5	7	2	12	53.01
MR 2	4	1	5	7	2	12	54.55
MR 3	4	1	5	8	4	12	51.98
LR 1	Not applicable						

Source: KARI (1996, Annex III)

No effort was made to include disintegration of adoption *d* as the final stage in a technology cycle because the adoption model did not provide this information. Also, it was commonly felt that asking experts to make prediction about the begin and slope of disintegration would be highly speculative. Further information was gathered on the time for technology development and the time span from the release of a technology to the beginning of its adoption.

3.8 Research Project Costs

The costs of a project normally consist of personnel, equipment, transport, inputs, land, and infrastructure. At the level of program planning, projects are often not sufficiently detailed to make precise estimates of the different cost components. It is assumed, therefore, that total costs are proportional to personnel costs that are normally more amenable to assessment. JANSSEN and KISSI (1997, p. 31) argue that it is acceptable to use human resource requirements as an approximation to estimate all other cost components since the costs of human resources make up the major share of most research budgets, and many of the operational costs (e.g., transport, production inputs) are linked with the time commitment that researchers are making.

To assess personnel costs, the time requirement of each activity in a project must be known for the different disciplines. This requires a distinction to be made of the different activities of a project and the disciplines involved. Once the research projects are defined, the time requirements of the different disciplines can then be assessed. This is most easily done in terms of months of research time per year. To calculate overall personnel costs, salaries payable to the different disciplines, time requirement and duration of the project in years has to be assessed (see Table 3-9).

Table 3-9: Research costs for the dairy project "development and utilisation of diets of heifers and cows using locally available feedstuffs"

Required scientists		part time (1/2) full time (1)	Year 1	Year 2	Year 3	Year 4	Year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Nutritionist	2	0.5; 1	12	24	24				1,000,000
Agronomist	1	1; 0.33; 0.5	12	4	6				366,666
Socio-economist	1	0.25	3	3	3				150,000
Average costs for one scientist / year		Discipline: All		200,000				**Sub-total**	**1,516,666**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials		equipment	transportation			
			M		M	M			
			341,401		544,635	1,696,543		**Total**	**4,099,246**

Source: Data compiled from KARI (1996, Annex III)

As can be seen from the lower part of Table 3-9, field trials, equipment and transportation were taken to represent the most important cost components apart from personnel costs. As opposed to what has be said earlier, KARI’s operational costs exceed personnel costs by far when the whole institution is considered.[8] However, latter costs have been used as an index of the cost structure for the 19 dairy research projects. Experts were asked to define project's specific commitment to equipment, field trials, transportation costs in terms of low, medium and high intensity (Table 3-10). This way, some flexibility was added concerning the cost shares between personnel and other cost components.

[8] Information on the cost structure at KARI was gathered from an internal KARI publication.

Table 3-10: Cost shares for different research cost components

	KARI's institution wide operational cost share in relation to personnel costs (1994)	Assumed operational cost shares in relation to personnel costs for different intensity levels		
		Low intensity 25 %	Medium intensity 100%	High intensity 175%
Equipment	35.91 %	8.98 %	35.91 %	62.84 %
Field trials	22.51 %	5.63 %	22.51 %	39.4 %
Transportation	111.86 %	55.93 %	111.86 %	167.79 %

3.9 The Economic Gains from Dairy Research: Analytical Framework

The economic effects of research is most commonly assessed through the use of cost-benefit analysis and economic surplus approaches. The specific characteristics of the Kenya dairy market suggested the application of an economic surplus framework similar to that of DAVIS, ORAN, and RYAN (1987), MILLS et al. (1995) and ALSTON et al. (1995) used for priority setting in agricultural research. The model developed for the present analysis is a partial equilibrium regional market model within which the economic gains attributable to a dairy research project are quantified in terms of an increase in producer surplus (PS), consumer surplus (CS) and, when government interventions are present, in terms of government surplus (GS). Commodity supply and demand curves are specified for different regions within Kenya and shifted over time by research and other factors. The analytical framework of the market model can be found in ALSTON et al. (1995, p. 387 ff.). The major specifications to be applied to the Kenyan dairy market can be summarised as follows:

- Linear demand and supply functions define a single commodity market framework (milk) with no linkages to other commodity markets (e.g., beef market) via cross-price elasticities.

- Trading activities are restricted to the different regional markets within the country, while no exporting and importing activities are assumed with other countries. This leads to a closed-economy situation where prices and quantities are determined internally.

- Regional markets are interlinked via price spillover effects. Milk and dairy products are assumed to be traded in significant quantities over long distances across regions.

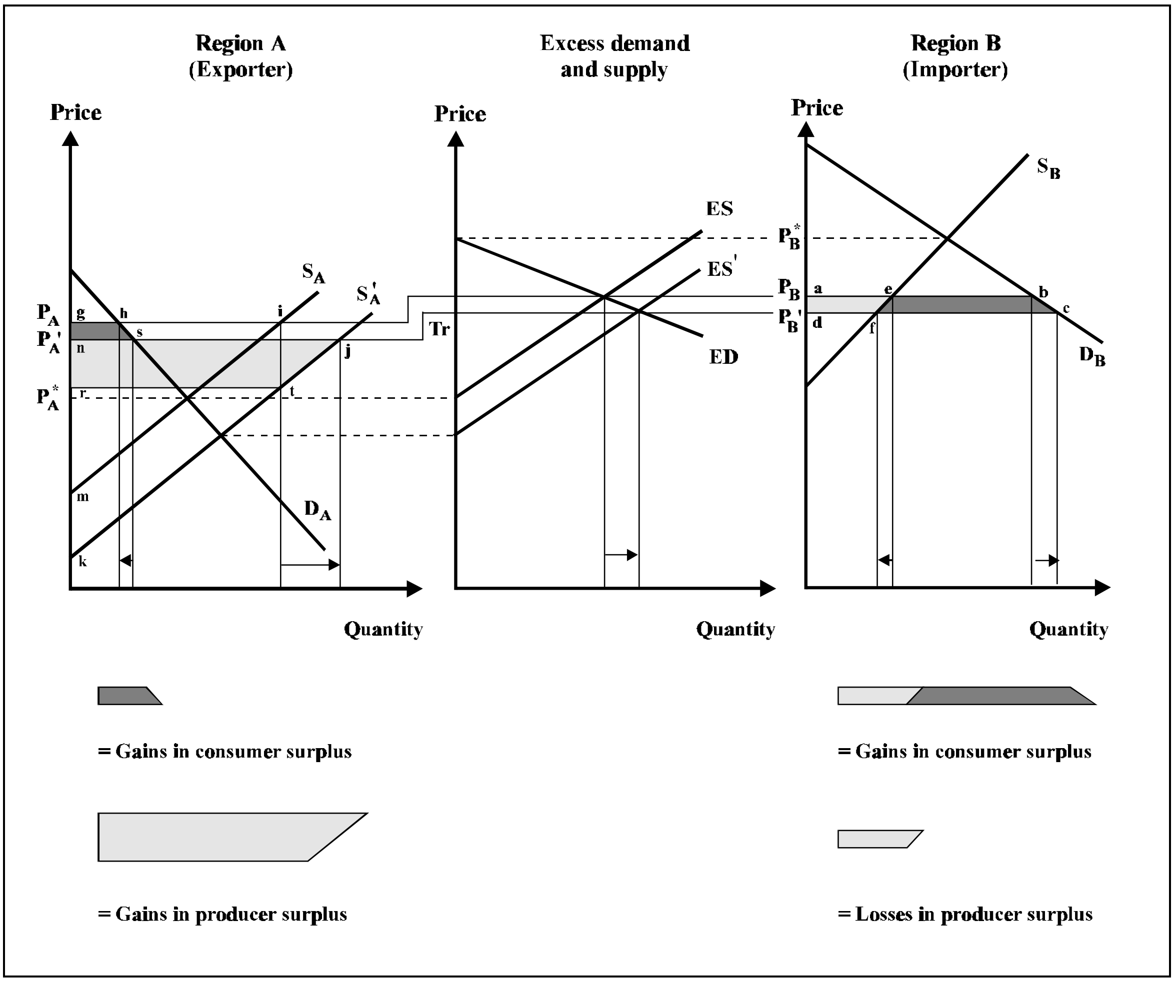
Thus, research induced changes in regional production and prices may affect prices and quantities in other regions.

- The dynamic elements of agricultural research are accounted for: the specific time profiles for technology generation and adoption, variable prices across regional markets, and multiple periods to aggregate annual economic gains over time (30 years) and regions.
- Exogenous demand and supply growth are included contributing to the effects of population and income dynamics as well as to external factors, besides research, that influence production.

The market framework does open the possibility to account for the heterogeneity of the research environment within a country and can capture major distributional effects of research and technical progress among adopting and non-adopting regions. The economic impact of research is measured as the gains in economic surplus due to a rightward shift in the supply schedule accruing to producers and consumers as well as to different regional markets. Three different parameters need to be considered to estimate the size of the annual shift in the supply schedule: probability of research success, annual adoption rates, and expected net yield increase. By combining economic surplus estimates over time and regions and by further subtracting research costs, it is possible to calculate net present value and cost-benefit ratio as final indicators of the potential economic gains from research investments.

The theoretical background of the multi-region market model used for the calculation of economic surplus estimates including spatially linked markets and transmission of price effects can be best illustrated using a two-region model as depicted in Figure 3-7 below. The market scenario assumes a parallel supply shift in an exporting region A due to research and examines the implications on prices, quantities and welfare on the exporting region A and importing region B. The exporting region A and the importing region B are represented in Figure 3-7 with their domestic demand (D_A, D_B) and supply (S_A, S_B) schedules generating excess demand (ED) and supply (ES) schedules. ED is the quantity consumers in region B would be prepared to buy in excess of that supplied by their domestic producers (S_B) at prices below the equilibrium closed-region price (P_B^*). ES represents the quantity available for export by region A at each price above the closed-region price P_A^*. The intersection of ED and ES determines the equilibrium price P_B and the quantity exported by region A and imported by region B. Under assumptions of transport costs (TR) of shipping export quantities from region A to region B the equilibrium price in region A (P_A) can be calculated as the price P_B in region B minus the transport costs TR.

Figure 3-7: Two-region market model with price spillover effects



Source: Modified, after DAVIS et al. (1987, p. 12)

A research induced shift in the supply schedule in the exporting region *A* from S_A to S_A' causes prices in both regions to fall from P_B to $P_B{}'$ in region *B* and from P_A to P_A' in region *A*. The reduction in the overall price level increases export quantities in region *A* coupled with a correspondent increase in imports in region *B*. The total benefits to research are measured as the shaded areas. Both regions gain in terms of increase in economic surplus. Consumers in both region *A* and *B* benefit due to reduced domestic prices. Producers in region *A* gain by the difference in the two producer surplus triangles. That is, the area "*njk-gim*" which is the same as the area "*njtr*" in case of a parallel supply shift. However, producers in region *B* lose as a result of research taking place in region *A*. This is because their production costs do not change but the price of their output fall. On the whole, region *B* can capture a net benefit because the gains to consumers outweigh losses suffered by producers.

The algebraic formula for the shaded area in Figure 3-7 can be developed with the assumptions of linear demand and supply functions and parallel shifts in the supply schedules resulting from research. The derivation of these formulae while extending the model to multiple *k* regions and *n* years is presented below.

The initial region specific linear supply and demand functions are defined as:

(1) $Q_{Sit} = a_{it} + b_i P_{Sit}$

(2) $Q_{Dit} = g_{it} + d_i P_{Dit}$

with subscript *i* denoting individual regions *i* and subscript *t* the year. From the supply and demand prices, quantities and elasticities, the initial intercepts and slopes of the market functions for each region *i* can be easily calculated as:

(3) $a_{i0} = (1 - e_{i0})\, Q_{Si0}$ $\quad b_{i0} = e_{i0}\, Q_{Si0} / P_{Si0}$

(4) $g_{i0} = (1 - h_{i0})\, Q_{Di0}$ $\quad d_{i0} = h_{i0}\, Q_{Di0} / P_{Di0}$

where e_{i0} = the elasticity for region *i* at time t = 0, and h_{i0} = the demand elasticity for region *i* at time t = 0. Including exogenous supply and demand growth as average exponential growth rates, the intercepts a and g for the successive years can be stated as:

(5) $a_{it} = a_{it-1} + p^{Qs}_i Q_{Sit-1}$ $\quad$ where p^{Qs}_i = exogenous supply growth for region *i*

(6) $g_{it} = g_{it-1} + p^{QD}_i\ Q_{Dit-1}$ $\quad$ where p^{QD}_i = exogenous demand growth rate for region *i*.

To model the with-research case (denoted with hyperscript "*R*" for all relevant variables) the annual research shift factor S_{it} must be incorporated in the supply function as:

(7) $Q_S{}^R{}_{it} = a^R{}_{it} + b_i P_S{}^R{}_{it}$ $\quad$ where $a^R{}_{it} = a_{i0} + S_{it} b_i$

The annual shift factor S_{it} for every period *t* and zone *i* is simply calculated as the product of the probability of research success *RS* = prob. ($YI_i \geq YI_{th,\, i}$) in zone *i*, expected net yield increase $YI_{e,i} = E(YI_i \mid YI_i \geq Yi_{th,i})$ in zone *i*, adoption rate (AR_{it}) for the specific period *t* and zone *i*, the initial (pre-shift) zonal price level (P_{i0}), divided by the zonal elasticity of supply e_{i0}. Expressed in terms of a proportionate and horizontal supply shift, S_{it} takes then the form:

(8) $S_{it} = \text{prob. } (YI_i \geq YI_{th,\, i}) \times E\,(YI_i \mid YI_i \geq YI_{th,\, i}) \times AR_{it} \times P_{i0} / e_{i0}$

The with-research demand function is denoted as:

(9) $Q_D{}^R{}_{it} = g^R{}_{it} + d_i P_D{}^R{}_{it}$

Regional prices are specified in terms of a reference price $P_{(ref)}$ net of a price wedge Tr_i representing transport and all other related transactions costs for shipping surplus quantities into deficit regions. Usually, the reference price $P_{(ref)}$ is defined as the market price with the highest price level. The price wedges Tr_i between regions are assumed to be constant over time.

(10) $$P_{it} = P_{(ref)\,t} - Tr_i$$

A variety of price policies can be included into the formula for the regional prices by defining *per unit* taxes and subsidies on consumption and/or production in the different regions Defining T^S_{it} as per unit consumer tax in region i at time t, and T^D_{it} as per unit producer tax in region i at time t, the different price policy regimes can be represented as different combinations of taxes and subsidies (ALSTON et al. 1995, p. 391), for example:

(11)

a consumption tax in region *i* at T_i per unit:	$T^S_i = T_i$;	$T^D_i = 0$
a production tax in region *i* at T_i per unit:	$T^S_i = 0$;	$T^D_i = T_i$
an export tax in region *i* at T_i per unit:	$T^S_i = -T_i$;	$T^D_i = T_i$
an import tariff in region *i* at T_i per unit:	$T^S_i = T_i$;	$T^D_i = -T_i$

The new regional prices including taxes to producers T^S and consumers T^D are calculated as:

(12) regional producer price: $$P_{S,i} = P_{(ref)} - Tr_i - T^s_i$$

regional consumer price: $$P_{D,i} = P_{(ref)} - Tr_i + T^D_i$$

The sample principle applied to subsidies which can be understood as negative taxes. So, it is possible to use the combination scheme to represent subsidies on production, consumption, exports, or imports. Accounting for the new regional prices the initial supply and demand functions without research (formulae 1 and 2) and with research (formulae 7 and 9) may be rewritten as:

(13) without-research case: $$Q_{Sit} = a_{it} + b_i\,(P_{(ref)\,t} - Tr_i - T^S_{it})$$

$$Q_{Dit} = g_{it} + d_i\,(P_{(ref)\,t} - Tr_i + T^D_{it})$$

(14) with-research case: $$Q_S{}^R_{it} = a^R_{it} + b_i\,(P^R_{(ref)\,t} - Tr_i - T^S_{it} + S_{it})$$

$$Q_D{}^R_{it} = g^R_{it} + d_i\,(P^R_{(ref)\,t} - Tr_i + T^D_{it})$$

For each period the sum of the quantities consumed must be equal to the quantity produced (market clearing rule) for the with-research and without-research cases:

(15) $$\sum_{i=1}^{k} Q_{Sit} = \sum_{i=1}^{k} Q_{Dit} \text{ and } \sum_{i=1}^{k} Q^{R}{}_{Sit} = \sum_{i=1}^{k} Q^{R}{}_{Dit}$$

The equilibrium reference prices for the without-research and with-research case given market clearing condition are:

(16) $$P^{*}{}_{(ref)\,t} = \Big\{ \sum_{i=1}^{k} (a_{it} - g_{it}) - \sum_{i=1}^{k} b_i\,(Tr_i + T^{S}{}_{it}) + \sum_{i=1}^{k} d_i\,(Tr_i - T^{D}{}_{it}) \Big\} \Big/ \sum_{i=1}^{k} (d_i - b_i)$$

(17) $$P^{R*}{}_{(ref)\,t} = \Big\{ \sum_{i=1}^{k} (a^{R}{}_{it} - g^{R}{}_{it}) - \sum_{i=1}^{k} b_i\,(Tr_i + T^{S}{}_{it} - S_{it}) + \sum_{i=1}^{k} d_i\,(Tr_i - T^{D}{}_{it}) \Big\} \Big/ \sum_{i=1}^{k} (d_i - b_i)$$

To check the signs intuitively, taxes on production in all regions ($T^{S}{}_{it}$) will raise the equilibrium price ($P^{*}{}_{(ref)\ t}$) while taxes on consumption ($T^{D}{}_{it}$) will lower it. The same holds true for the equilibrium price with research ($P^{R*}{}_{(ref)\ t}$). From these equilibrium prices the regional prices and quantities can be calculated. Then, the annual regional changes in total economic surplus ($\Delta\ TS$) and economic surplus by groups are as follows (ALSTON et al., 1995, p. 393):

(18)
$$\begin{aligned}
\Delta\, PS_{it} &= (S_{it} + P_S{}^{R}{}_{it} - P_{Sit})\,(Q_{Sit} + 0.5(Q_S{}^{R}{}_{it} - Q_{Sit})) \\
\Delta\, CS_{it} &= (P_{Dit} - P_D{}^{R}{}_{it})\,(Q_{Dit} + 0.5\,(Q_D{}^{R}{}_{it} - Q_{Dit})) \\
\Delta\, GS_{it} &= T^{D}{}_{it}\,(Q_D{}^{R}{}_{it} - Q_{Dit}) + T^{S}{}_{it}\,(Q_S{}^{R}{}_{it} - Q_{Sit}) \\
\Delta\, TS_{it} &= \Delta\, PS_{it} + \Delta\, CS_{it} + \Delta\, GS_{it}
\end{aligned}$$

where $\Delta\ PS_{it}$ = producer surplus in region i at year t

$\Delta\ CS_{it}$ = consumer surplus in region i at year t

$\Delta\ GS_{it}$ = government surplus in region i at year t and

$\Delta\ TS_{it}$ = total economic surplus in region i at year t.

The present values for the stream of producer (PV_{PS}), consumer (PV_{CS}), government (PV_{GS}) and total surplus (PV_{TS}) changes over all n years can be calculated as:

(19) $$PV_{TSi} = \sum_{t=1}^{n} (\Delta\, PS_{it} + \Delta\, CS_{it} + \Delta\, GS_{it}) / (1 + r)^{t}$$

where r is the real discount rate for the use of public sector financial resources. Surplus changes can then be combined additively across regions to assess either the within or across region impacts of spatially targeted research. By including discounted investment costs one can further calculate total net present value (NPV) and cost-benefit ratio (CBR) for a research project as:

(20) $$NPV_{TS} = \sum_{i=1}^{k} PV_{TSi} - \sum_{t=1}^{n} C_t / (1 + r)^t$$

(21) $$CBR = \frac{\sum_{i=1}^{k} PV_{TSi}}{\sum_{t=1}^{n} C_t / (1+r)^t}$$

The underlying assumptions of the regional model – linear market functions and parallel supply shifts – help to develop the model with simple algebra. As it was mentioned in Chapter 2, assuming linear functions as simplification does not markedly affect the size of the changes in total economic surplus compared to non-linear specification of the market functions. More of an issue for the size of the final benefits is the parallel supply shift which, however, is a fairly good approximation as long as there is some evidence that would advocate other shift types.

One real critical issue is that price differences across regions are held constant through the price wedge Tr_i which prevents possible reversal of trade flows and price swings between regions i.e., that an export region turns into an import region or vice versa. Failure to capture these price swings may generate unrealistic estimates of future commodity market conditions and distort estimates of potential agricultural research benefits. MILLS (1997) developed a modified trade model that accounts for such price swings and trade reversal among multiple regions. The direction of prices and trade flows between regions are determined by applying quadratic programming techniques. MILL's solution may have considerable appeal for deterministic models but poses major difficulties for stochastic models that will be introduced in a later chapter (e.g., in conjunction with Monte Carlo simulation) due to a large number of iterative model runs.

3.10 The Economic Gains from Dairy Research: Results

The following section presents the basic results of the national priority setting workshop at KARI including the list of proposed research project types and their expected performance expressed in terms of net present value and cost-benefit ratio. KARI dairy experts identified nineteen project types: nine projects fall into the "feed resources and utilisation" thrust, six projects are concerned with "animal heath", two projects with "breeding and genetic improvement" and another two projects are non-technical and relate to "socio-economic" research. The majority of the projects pursue applied research reflecting KARI’s primary research mandate in conducting applied rather than basic research. Projects in the "animal health" thrust are rather small in size and require little research resources while projects in the "feed resource and utilisation thrust" are designed at a larger scale and, consequently, are more resource demanding. The results on the expected economic gains for each dairy research project were derived from the regional market model as described in the preceding section. The input data set consisted of regional prices and quantities to determine the supply and demand functions of each regional market, the individual parameters for the research induced supply shifts by region and years, and research costs. Additionally, the following assumptions were made, including:

→ medium-term supply elasticity of 0.5 per cent for all dairy regions. KIRORI and GITU (1991, p. 27) calculated a short-run supply elasticity of 0.137, and a long-run elasticity for dairy of 0.684 for the whole country;

→ medium-term demand elasticity of -0.5 per cent;

→ exogenous demand increase of 2 per cent based on a 2.5 per cent average population increase per annum in Kenya;

→ no exogenous production increase during the time period under consideration; and

→ a real discount rate of 10 per cent which reflects the long-term real interest rate on government funds for agricultural research.

Table 3-11 highlights the expected research benefits expressed in net present value and cost-benefit ratio of all 19 projects. It can be seen that ranking projects by the size of net present value or by cost-benefit ratio yield different results. The top 5 projects with the highest NPV belong to "feed resources and utilisation". KARI’s experts have given high values on adoption rates and potential yield increase across the major target zones, but also have recognised the relatively high resource requirement.

The two most profitable project types with respect to CBR are targeted at animal health issues such as the "cow fertility" project (RP 11) and the "ECF immunisation" project (RP 12). These two projects are relatively small, and significant improvement can be achieved with a limited effort.

The next following projects fall in the "feed resources and utilisation" thrust, and are concerned with the "development and utilisation of diets for heifer and cows" (RP 3) and with "forage production and utilisation techniques" (RP 4). Both projects are considered to require sizeable resources but, on the other hand, are expected to have high benefits. Significant benefits are expected from the two socio-economic projects: "policy environment studies of milk marketing" (RP 18 and RP 19). It was argued that "improved milk marketing strategies" as the outcome of the two socio-economic study projects, if recognised and put in practise by policy makers, was estimated to have a considerable effect on higher farm gate prices and improved cost efficiency in the dairy market.

Table 3-11: Research project types, research costs and economic gains expressed in terms of net present value and cost-benefit ratio

Thrust	Project No.	Project Type	Net present value	Research costs (discounted)	Cost-benefit ratio
			KSh million	KSh million	
FR	RP 1	Development and utilisation of calf feeds; economics of feeding commercial feeds	127.56	3.473	37.73
FR	RP 2	Development and utilisation of calf feeds; development of locally available calf feeds	395.86	4.362	91.76
FR	RP 3	Development and utilisation of diets of heifers and cows using locally available feedstuffs	12,022.28	3.249	3,701.86
FR	RP 4	On-farm testing and adaptation of recommended forage production and utilisation techniques	12,021.78	4.062	2,960.29
FR	RP 5	Introduction and evaluation of forage varieties suitable for frost prone areas	125.44	1.503	84.47
FR	RP 6	Improvement of feed quality through processing and forage legume utilisation	7,340.22	6.674	1,100.89
FR	RP 7	Development of forage / food crop intercropping systems	12,790.13	3.884	3,294.38
FR	RP 8	Improvement of feed conservation techniques and determination of feed availability year-round	3,186.38	3.834	832.03
FR	RP 9	Development of forage legume seed production technology	4,745.87	4.498	1,056.12
AH	RP 10	Development of appropriate calf housing and studies on *HELMINTH* diseases	1,149.29	0.546	2,105.06
AH	RP 11	Studies of cow fertility problems; causes and possible solutions	6,498.20	0.702	9,253.91
AH	RP 12	On-farm testing of ECF-immunisation	2,511.19	0.312	8,046.39
AH	RP 13	Practical mastitis control	973.73	0.440	2,215.90
AH	RP 14	Indigenous disease control methods (Ethnovet)	2,403.58	3.371	714.05
AH	RP 15	Development of alternative or improved delivery system for assisting health service	7,496.12	11.250	667.29
BR	RP 16	Development of more productive breeds for zero / semi-zero grazing systems	2,829.69	5.814	487.71
BR	RP 17	Development of more productive breeds for free grazing systems	679.30	5.814	117.84
SE	RP 18	Policy environment study of milk marketing (government option)	5,007.16	3.079	1,627.35
SE	RP 19	Policy environment study of milk marketing (private option)	6,774.55	3.079	2,201.40

FR = Feed resources and utilisation; AH = Animal health; BR = Breeding and genetic improvement; and SE = Socio-economics

However, the accuracy of the socio-economic projects tend to be lower than for the technical projects due to a high degree of subjectivity and rather divergent opinions in the "socio-economics" working group.

3.10.1 Research Benefits Across Regional Markets

The expected benefits aggregated over all dairy research projects are distributed across the regional markets in close accordance with the share of dairy production in these regional markets. This means: Major dairy production regions also capture large shares of the expected benefits, while benefits are relatively small for the minor important dairy regions. However, some differences can be observed as outlined in Table 3-12. The high rainfall/medium temperature zone HR 2 captures around 36.2 per cent of the expected benefits, which is a larger share than the share of production (26.6 per cent), and thereby indicating the suitability of this zone for the proposed dairy research projects. Likewise, the medium temperature/medium rainfall zone MR 2 concentrates around 30 per cent of the total benefits which is significantly higher than its production share of 23.7 per cent.

Table 3-12: Research benefits across regional markets expressed in terms of present value (KSh million)

		Total		Feed resources and utilisation		Animal health		Breeding		Socio-economics	
		Present value	%	Present value	%	Present value	%	Present value	%	Present value	%
Nairobi, Mombasa, and other urban areas		4,976	5.58	2,710	5.13	1,370	6.51	296	8.40	600	5.09
HR 1	High rainfall/ low temperature	6,071	6.81	3,429	6.50	1,531	7.28	233	6.61	878	7.45
HR 2	High rainfall/medium temperature	32,270	36.20	21,301	40.35	6,427	30.53	1,085	30.81	3,457	29.32
MR 1	Medium rainfall/ low temperature	9,834	11.03	5,256	9.96	2,619	12.44	345	9.79	1,614	13.70
MR 2	medium rainfall/medium temperature	26,459	29.68	18,300	34.67	4,754	22.59	762	21.66	2,642	22.41
MR 3	medium rainfall/ high temperature	2,394	2.69	1,283	2.43	658	3.13	122	3.47	331	2.81
LR 1	Low rainfall/medium temperature	7,145	8.01	511	0.97	3,690	17.53	678	19.26	2,266	19.23
Total		**89,148**	**100**	**52,791**	**100**	**21,049**	**100**	**3,521**	**100**	**11,788**	**100**

Less promising is the high temperature/medium rainfall zone MR 1 with a benefit share of 11 per cent which is significantly lower than the corresponding production share of 20.54 per cent. This indicates that this zone has a relatively low potential for research. The remaining three zones HR 2, MR 1 and MR 2 perform differently due to experts' differentiation of yield increase and adoption estimates by zonal (regional) characteristics. This is especially true for projects from the "feed resources and utilisation" thrust. All three zones take around 77 per cent of all possible research benefits, thereby establishing them as the core zones for the national dairy program.

In order of decreasing benefits, the first three zones are being followed by the LR 1, HR 1 and MR 3. Except for zone MR 3, these zones perform worse than their production shares which is a consequence of the experts' general judgement that potential impact is rather low for a variety of research types. A rather small benefit share goes to the major cities (only 5 per cent) as consumer surplus from decreasing milk prices and higher consumption. However, these benefits are not essential for prioritising dairy target zones and research types. Results by thrusts and zones tend to follow the general pattern of the total benefits by zones. Nevertheless, some minor differences exist for example, benefits from the "feed resources and utilisation" thrust tend to be proportionally larger in the core zones than in the other zones; however, the remaining thrusts have relatively high benefit shares in the less important zones MR 2, LR 1 and HR 1.

A more detailed view on the distribution pattern of the research benefits across regions reveal strong differences among individual dairy projects. Table 3-13 presents the present values by project type and region, excluding research costs which could not be differentiated by the project's resources allocated to each region. Zonal (regional characteristics) had a major influence on the expert's elicitation of net yield increase and technology characteristics from which adoption rates were derived. This can be studied from the elicitation information outlined in Appendix *A*. Consequently, the size of the supply shifts and the generated economic surplus gains differ markedly across regions and projects. One interesting finding is that some regions would even face economic losses due to research conducted in other regions (e.g., for RP 4, RP 9, and RP 17). These cases have in common the tendency that large supply shifts occur in regions with low dairy production and small shifts in large production regions. This leads to losses in producer surplus in the large production regions which cannot be offset through gains in consumer surplus.

Table 3-13: Research benefits by project type and regional market expressed in terms of present value (KSh million)

	Nairobi, Mombasa, and other urban regions	HR 1	HR 2	MR 1	MR 2	MR 3	LR 1	Total
RP 1	0.00	5.24	16.21	11.80	14.13	7.20	76.45	131.03
RP 2	62.59	19.80	137.61	6.64	26.01	23.70	123.88	400.22
RP 3	568.44	1,431.97	6,141.97	129.81	3,328.30	354.22	70.82	12,025.53
RP 4	581.87	-121.02	6,270.89	1,428.91	3,596.08	198.30	70.81	12,025.85
RP 5	0.00	126.94	0.00	0.00	0.00	0.00	0.00	126.94
RP 6	361.72	375.48	2,719.70	1,270.28	2,499.99	80.35	39.38	7,346.89
RP 7	616.63	1,454.87	4,954.38	2,359.42	3,202.26	127.63	78.83	12,794.01
RP 8	250.11	195.41	912.28	345.36	1,289.06	173.73	24.26	3,190.21
RP 9	268.85	-59.24	148.35	-296.39	4,344.61	317.42	26.77	4,750.36
RP 10	120.54	70.02	364.47	84.66	243.51	44.33	222.30	1,149.83
RP 11	301.62	482.40	1,866.57	903.93	1,439.15	175.31	1,329.92	6,498.90
RP 12	238.31	159.25	784.98	214.33	537.63	91.98	485.01	2,511.50
RP 13	106.60	58.24	310.65	66.63	205.31	38.35	188.38	974.17
RP 14	204.71	206.54	890.74	341.17	650.15	93.64	19.99	2,406.95
RP 15	398.34	554.88	2,209.17	1,008.19	1,678.19	214.62	1,443.99	7,507.37
RP 16	196.95	254.48	1,031.36	453.91	776.59	102.10	20.12	2,835.50
RP 17	98.91	-21.85	53.43	-109.16	-14.13	19.96	657.96	685.12
RP 18	270.66	368.96	1,476.54	667.11	1,119.21	144.08	963.70	5,010.24
RP 19	328.85	508.91	1,980.23	947.27	1,522.61	187.15	1,302.61	6,777.63

HR 1 = high rainfall/ low temperature; HR 2 = medium rainfall/ low temperature; MR 1 = medium rainfall/ high temperature; MR 2 = medium rainfall/medium temperature; and LR 1 = Low rainfall/medium temperature agro-ecological zone

3.10.2 Research Benefits by Thrust

The aggregation of research benefits by thrust gives a clear indication of the superiority of the "feed resources and utilisation" with almost 60 per cent of the benefits falling in this category (see Table 3-14). This is partly due to the large number of research types (9 out of 19 project types) but also to the outstanding performance of most projects in this thrust. Animal health is the second most important thrust with a benefit share of around 23.6 per cent, followed by "socio-economics" and "breeding and genetic improvement". The "socio-economics" thrust with the two single research projects "policy environment study" captures a significant share as a result of expected the high pay-off. But careful interpretation of the socio-economic projects is recommended. Many workshop participants felt that project details were not sufficiently specified, thus leaving only a vague picture of the intention and scope of these projects.

Table 3-14: Research benefits and costs by research thrust

Thrust	Net present value		Research costs (discounted)		Cost-benefit ratio
	KSh million	%	KSh million	%	
Feed resources and utilisation	52,755.51	59.22	35,538	50.81	1,484.50
Animal health	21,032.10	23.61	16,622	23.76	1,265.35
Breeding and genetic improvement	3,508.99	3.94	11,628	16.62	301.77
Socio-economics	11,781.72	13.23	6,158	8.80	1,913.38
Total	**89,078.32**	**100**	**69,945**	**100**	**1,273.55**

Some general remarks on the accuracy of the results are worth making. A common phenomenon can be observed here which is that experts tend to overestimate the expected research benefits as indicated by extremely high cost-benefit ratio. This is mainly due to unrealistic assumptions regarding annual yield increase effects. In reality, the size of a country's research induced production increase per year rarely exceeds 10 per cent, more realistically it may range between 1 and 5 per cent. Even then, research performance would be extraordinary since it could fully compensate increased milk demand due to population. To work with more realistic figures, one would have to scale down expected benefits by a common factor while preserving the relative projects' performance. However, this proposal was not put forward to the KARI management.

4 Limitations of the Case Study and Opportunities for Methodological Improvements

4.1 Critical Assessment of the Dairy Research Case Study

The Kenyan Agricultural Research Institute (KARI) and the collaborative institutions such as the International Service for National Agricultural Research (ISNAR) and the Humboldt University Berlin (HUB) have invested much time and resources in the priority setting exercise for the national dairy research program. As a result of the involvement of these institutions the priority setting exercise discriminates against other examples due to its heavy scientific "load" from applying several new and innovative approaches. For example, much effort was spent on developing a spatial scheme of dairy target zones, estimating research parameters, and eliciting research objectives and their relative importance using the AHP. Likewise, the use of an adoption prediction model and the application of a complicated market model underline the extra effort that goes beyond usual practise. Consequently, the amount of information on the potential impact from the dairy research projects which are differentiated across different regions, consumers and producers, urban areas and the rural areas, is impressive.

In order to turn priority setting into concrete changes for the dairy research program further working steps are required to proceed from research evaluation to concrete decisions on future plans and the direction of the dairy research program. Evaluation results must be synthesised to arrive at recommendations on the choice of research projects to be added to the research program. Recommendations must be approved, actions plans must be developed, and proposals for fund raising as well as the creation of an appropriate institutional framework must be prepared. All these additional working steps are solved by internal consultation and discussion rounds among the members of the research management. Like the majority of priority setting examples this exercise ended with the presentation of the evaluation results, project ranking and broad recommendations on the allocation of resources.

However, as argued earlier, the development of concrete research plans from evaluation information is a complex task because it involves multiple research objectives, divergent interests of decision makers, institutional restrictions, and uncertainty in the impact estimates of the research investments. Take this case study as an example. Managers at KARI may need to take into account the resources requirements of KARI's numerous affiliated national and regional research centres, or the specific funding pattern of the dairy program's research thrusts. Another difficulties may arise from the current composition of KARI's scientific staff and the particular unfavourable situation in Kenya to recruit scientific staff that would be needed to implement some of the planned dairy research projects. Also, the management of transportation facilities, laboratories, and other research hardware may pose major problems in research planning because they constitute limitational resources but, at the same time, should work at full capacity in order to avoid high fixed costs. As research planning often goes, many issues and concerns of these types are brought in and need to be thoroughly discussed. As a result, the final decisions on the types of projects to implement are hardly the same as those recommended from evaluation results and ranking lists. Priority setting procedures of similar types to that applied in the case study are deficient in providing guidance to such complex and fussy decision problems.

Another methodological shortcoming of the case study is the ignorance of the uncertainty that inevitably surrounds the estimation of research parameters in any ex-ante analysis. However, most research parameters in the case were quantified as deterministic single-value estimates where, in fact, they should have been treated as uncertain, thus stochastic variables. Only net yield increase has explicitly incorporated uncertainty by constructing a probability distribution around the range of possible values but has finally been "degenerated" to a quasi-deterministic parameter represented through its expected value. This has lead to a deterministic specification of the economic surplus model and resulted in deterministic values for the expected gains from dairy research. Using a deterministic system for research evaluation, as it was done in our case study, has several disadvantages compared to a stochastic system:

- it implies a complete loss of information regarding the uncertainty and riskiness of individual research activities. If the riskiness of the individual projects is not explicitly stated in quantitative or qualitative terms, then managers are unable to assess, control, and reduce the riskiness of the resultant research plans through modifications in project design or size.

- A deterministic evaluation system forces experts to exert precision in their judgement on the likely effects of research by attaching a single value where, if fact, the effects are highly conjectural. The lack of information and knowledge of complex research interactions coupled with the external uncertainty surrounding the research system should lead to an assessment procedure where experts are given more liberties to place their subjective judgement within a range of possible values.

- A deterministic evaluation creates "faked" objectivity when analysts present their deterministic impact results and outline their recommendations to the auditorium of research managers and decision makers. Intuitively, evaluation results are perceived as "facts" if analysts do not explicitly comment on the subjectivity and uncertainty in their model assumptions. Since subjective judgement and incomplete knowledge are the base input information, evaluation results cannot pretend to be more precise than what has been brought in.

A first impression of the uncertainty surrounding the elicitation process for the dairy research projects defined in the case study is given in Table 4-1. It shows that experts have perceived the influence of unpredictable external factors on the stability of the net yield increase estimates as being very specific to the type of dairy research. In absolute terms the value range is greatest among projects of the feed resources and utilisation thrust, and lowest for projects from the animal health thrust. The assumed variability in relation to the expected value (variation of coefficient) is somewhat less divergent.

Table 4-1: Uncertainty in the elicitation of the net yield increase in the "high rainfall 2" zone for selected research projects

Thrust	Project title	Project number	Net yield increase estimates *		
			lowest value	most likely value	highest value
Feed resources and utilisation	Development and utilisation of diets for heifers and cows using locally available feedstuffs	3	16.5	33	50
Feed resources and utilisation	On-farm testing and adaptation of recommended forage production and utilisation techniques	4	22 (12)	44.67 (34.67)	66.67 (56.67)
Animal health	Development of appropriate calf housing and studies on *HELMINTHS* disease	10	0 (-1.5)	6 (4.5)	10 (8.5)
Animal health	On-farm testing of ECF-immunisation	12	3 (2.5)	5(4.5)	7 (6.5)
Breeding and generic resources	Development of more productive breeds for zero/ semi-zero grazing systems	16	5 (3.75)	10 (8.75)	15 (13.75)
Animal health	Policy environment study of milk marketing (government option)	18	4	8	25

* Number in brackets are corrected net yield increase estimates

In light of these argument the application of some formal methods that have found widespread use in business management to this priority setting case study may be very beneficial. Numerical simulation and stochastic dominance analysis are such methods where uncertainty can be formally included into the economic evaluation system and research projects can be compared based on economic performance and riskiness.

4.2 Mathematical Programming Models as Decision Aid in Priority Setting for the Dairy Research Program

In the field of agricultural economics, mathematical programming models are most prominent in farm business management. However, they can be easily adapted to research decision problems such as those outlines in the preceding sections. Mathematical programming (MP) comprises a set of various techniques dealing with different aspects and complexity of a decision problem. According to the classification scheme of decision making problems by KEENEY and RAIFFA (1993, p. 27) in Figure 4-1, all four decision classes can be addressed through various mathematical programming techniques. For solving a deterministic decision problem, linear programming and multi-objective programming are suitable techniques and are easiest to apply. More demanding are techniques that are capable of dealing with uncertainty such as utility efficient programming and quadratic risk programming, but can also include multiple objectives simultaneously.

Figure 4-1: Mathematical programming techniques for different decision making categories

Decision making category	Single objective	Multiple objectives
Certainty	**Linear programming (LP)**	**Multi-objective programming (MOP)**
Uncertainty	**Risk programming (RP)** → **Utility efficient programming (UEP)** → **Quadratic risk programming (QRP)** → **MOTAD programming (MOTAD)**	**Risk programming (MAUT)** → **Utility efficient programming (UEP)**

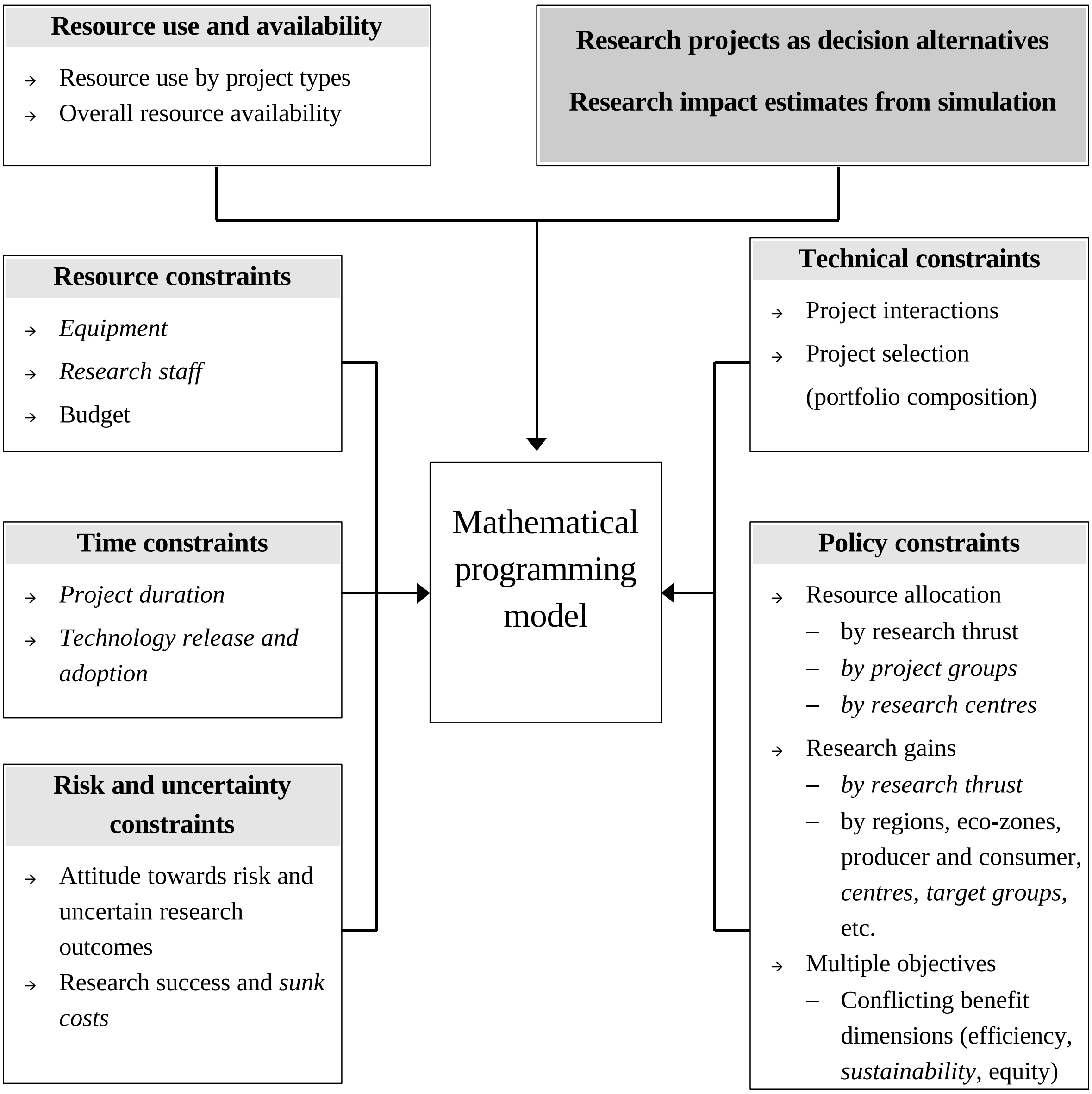
Mathematical programming is based on the fundamental economic principle of optimisation subject to constraints. In research planning such as priority setting, mathematical programming models describe the decision problem generally as one of selecting research alternatives, may be research projects or whole research programs, so as to optimise a given objectives function including one or several objectives while satisfying the imposed constraints. Procedures for such a research portfolio decision problem vary considerably and depend on the characteristics of the optimisation problem in terms of the objective function to be maximised, the relationships between changes in research activities and the value of the objective functions and constraints. Applied to the specific conditions of research priority setting, mathematical programming models open a broad perspective for dealing with complex planning and decision problems in agricultural research planning such as those outlined in the preceding section due to the wide spectrum of techniques. Figure 4-2 makes an attempt to summarise possible areas for investigation that can be formally included and dealt with as decision constraints in a mathematical programming framework. It should be noted that not all of them can be addressed and exemplified in the mathematical programming analyses of this study.

The first constraint type in Figure 4-2 relates to the institutional capacity for conducting research including the number and discipline of scientists and technical staff, research equipment, laboratory, transport facility, and the financial resources that can be spent on a commodity program. By changing assumptions regarding one or more of these components, several aspects can be examined: first, the different time horizons in the planning process, i.e., from short-term planning where capacity is rather fixed to long-term planning where capacity can be adjusted; furthermore, the critical bottlenecks in the institute's capacity to add new research activities, and finally; the potential incremental economic returns when e.g., new scientists are employed or external donors provide additional funds.

Time constraints concern the time dimension of the research activities. When deadlines or mid-term evaluation are imposed on the institution's achievement of preliminary research results, time constraints can be used to set upper limits to admissible research duration or technology diffusion. Risk and uncertainty constraints offer the possibility to specify decision maker's attitudes toward risk in a programming model in terms of a single risk aversion value or risk interval for sensitivity analysis. Another, but rather different aspect of research risk, may be addressed through imposing a critical limit on the probability of research failure or sunk costs for a proposed research plan. Although research success is taken into account indirectly in the economic surplus estimates, research management may wish to place stronger emphasis on risk of failure by defining constraints as upper limits on the risk involved.

Technical constraints deal with two common problems in R&D project selection models: *project interactions* and *project selection*. Project interactions describe the fact that two or more projects may not be independent of each other in terms of their individual cost, outcome or benefit. This means that individual project performance depends on the absence or presence of other projects in the proposed portfolio. Project dependencies can be accommodated through non-linear objective functions, or more simply through logic (Boolean) combination constraints. A project selection constraint imposes a limitation on the composition of the research portfolio and comes into play when mutually exclusive or inclusive choices must be made between projects. For example, projects may be similar in their objectives and characteristics, so that only one project should be considered, or projects may be adjunct, that is, they require each other for a successful completion of their intended objectives (mutually inclusive).

Figure 4-2: Analysis of planning and decision making aspects with mathematical programming in priority setting for agricultural research



* Constraint types in italics are not considered in the various mathematical programming analyses in chapters 5 and 7.

The most important constraint type directly addresses research policy issues. Formal decision support methods such as mathematical programming models are always driven by maximisation of objective function values and deliver solutions that are not satisfactory to the specific circumstances of the institute. Policy constraints can make the model more specific to the institute's organisational and managerial environment and can incorporate the different research agenda of the stakeholders.

As outlined in Figure 4-2, three policy areas can be distinguished: resource allocation, research gains and multiple objectives. Resource allocation is a policy area of practical importance to R&D managers where they can decide on a suitable budgeting strategy for the group of planned research projects between the two extremes: incremental and zero-base budgeting. In incremental budgeting, the set of planned projects should exhibit a similar budgeting pattern across research thrusts, project groups or research centres to the overall research program, however in zero-base budgeting, all previous and current allocations can be ignored. A budgeting strategy can be defined by upper and lower limits on the amount or share of budget for research thrusts or centres.

Constraints on research gains offer one possibility to incorporate various sorts of equity concerns between different regions, producers and consumers, or any other target groups. Constraints can be imposed on the distribution of research gains by defining upper or lower limits on absolute research gains or gain shares. Constraints on research objectives present yet another possibility to examine the trade-offs between objectives. By maximising one objective (e.g., efficiency) while imposing and varying constraints on the level of achievement for the other objective(s), one can perform quantitative trade-off analysis between conflicting objectives; this provides useful information on the opportunity costs of different research agendas.

4.3 Risk and Uncertainty in Priority Setting for Agricultural Research

4.3.1 General Approaches to Risk and Uncertainty

Agricultural research is an intrinsically risky activity. Uncertainty is encountered in virtually all steps of the research process: it is concerned with the effective implementation of planned research activities, inherent in the generation of worthwhile discoveries, present in the propagation of the new technologies through the extension service, and in the adoption of the research findings such as new production technologies, or crop varieties by farmers. Moreover, agricultural research takes place in an economic and social environment that is notoriously unstable. Especially in developing countries, the agricultural sector is characterised by underdeveloped agricultural markets, fluctuating market prices, weather induced production instabilities, insufficient provision of inputs and lack of marketing, infrastructure and facilities.

All these uncertainties create difficulties for almost all groups occupied with research: for research management to undertake long-term planning, for scientists to make decisions about their work and examine the research results in the fields, and for economists to measure the benefits and costs of research projects and programs. It seems that virtually no attention has been given by public or private research institutions to the presence of uncertainty in the research process and its environment. ANDERSON and DILLON (1992, p. 11 ff.) distinguish three different approaches towards risk and uncertainty. The most extreme possibility relating to risk is where decision makers and analysts are completely unconscious of it. Much of the extant (especially earlier) literature on agricultural science, economics and research seems implicitly to assume such a situation. Perhaps one good reason for the earlier neglect and lack of documentation was the poor state of development and appreciation of the languages of uncertainty (i.e., especially subjective probability).

Another possibility which is the most common approach to uncertainty in policy analysis is conscious recognition of the existence of risk but, for one reason or another, it is conveniently ignored or assumed away. QUADE (1975) has characterised this strategy as a "chronic disease of planners". Analysts taking this stance may assume, for instance, that they can arrive at a good decision though exploitation of a deterministic representation of a system or they may argue that the benefits of any accounting for risk through, perhaps better decision making, do not fully pay off for the additional costs involved in modelling and analysing a stochastic system.

Another position towards risk is the informal treatment of risk and subsumes a bundle of several approaches which cannot be pinned down very precisely. These approaches may have in common that planning is not based on expected values of uncertain quantities but on representative values such as "cautious" estimates of crop yields in farm planning or "conservative" time scheduling of planned research projects. In this position falls the more systematic elicitation of possible values with the intention of assigning something of the impact of the uncertainty on decision making based on traditional sensitivity analysis. The other extreme of handling risk is the formal modelling of risk which in fact can be attempted with varying intensity. It furnishes a more or less complete description of the risk in a system including the range of possible values of uncertain model variables as well as the likelihood of occurrence. The core of a formal treatment of risk and uncertainty is probability theory and decision theory. Several methods are used for modelling and propagation of risk in systems such as mathematical programming, investment appraisal, stochastic simulation and related techniques. Accounting for risk in investment analysis and more precisely in project appraisal is potentially a complex matter. Perhaps this explains why it has mostly been ignored in public investment analysis and, in particular, in research evaluation. As such no attempts have been made to critically assess the worthwhileness of considering risk in project planning and appraisal and how the simplification of a deterministic setting can lead to errorness statement of project's economic performance and hence wrong project approval. In this context, GITTINGER (1982, p. 29 ff.) mentioned that a "*major reason for the failure of agricultural development projects were poor project design and appraisal due to the underestimation of costs, the setting of excessively optimistic production targets and the failure to consider adequately such risk factors as climatic variability, changes of government priority for the agricultural sector and price uncertainty*".

However, some approaches to dealing with risk in project appraisal are available. These consist of approximating formulae for determining appropriate risk deduction from the expected values of the present worth of projects and of formal risk analysis methods for dealing with the technical side of risk and uncertainty. As outlined in ANDERSON and DILLON (1992. p. 73 ff.) the authors of the UNIDO guidelines (UNIDO 1992) on project appraisal supported the use of expected present value evaluated at the riskless social rate of discount as the normal practise but noted two exceptional cases for risk consideration. In such cases UNIDO recommended a small deduction from the expected PV for large-projects and potentially significant adjustments involved in accounting for correlation effects between project benefit and national income. For instance, a project with a strong negative correlation with national income such as a major flood-control or irrigation project may have a certainty equivalent benefit in excess of the expected present value, and conversely, positively correlated projects will be discounted for uncertainty.

LITTLE and MIRRLEES (1974) catalogued several more complicated cases when social expected present value may be inadequate as a performance criterion. They used concave utility functions over the present value scale to approximate the calculation of risk-adjusted (certainty equivalent benefit) project benefits. To specify the degree of risk aversion embodied in the utility function they used a dimensionless coefficient of relative risk version. Thus, if risk is involved, the budgeting of risky projects should be based on the expected utility rather than on the expected present value.[1] The more technical side of risk and

[1] A detailed description of different approaches for investment appraisal under risk can be found in ANDERSON et al. (1977, p. 249-275), and ANDERSON and DILLON (1992, p. 73 ff.).

uncertainty in project appraisal is outlined in REUTLINGER (1970) and POULIQUEN (1970). These authors first introduced a more sophisticated treatment of uncertainty using simulation techniques and probability theory. In contrast to the former approach in which adjustment to risk is essentially limited to deducting a certain amount from the project's present value while keeping the project analysis still deterministic, simulation techniques enter the scene as an aid to investment appraisal with explicit recognition of the uncertainty surrounding all relevant factors that have an impact on project performance. The application of simulation techniques in project appraisal has now become the cornerstone of what is known as formal (or quantitative) risk analysis.

4.3.2 Approaches to Risk and Uncertainty in Priority Setting for Agricultural Research

The acknowledgement of risk and uncertainty in research evaluation and priority setting has so far been unsatisfactory although most of the analysts, practitioners and managers in agricultural research are aware of risk and uncertainty. As ANDERSON (1992, p. 103) puts it: "*Most of the formal literature on agricultural research per se, whether of a managerial or evaluative orientation, implicitly treats research and its setting as being deterministic. In fact, of course, the process is intrinsically uncertain. Most agricultural sectors are highly variable and the observed variability is extremely unpredictable so that it is, technically speaking, risky. The conjunction of an uncertain research process with an uncertain physical and economic environment is the reality of agriculture that makes it all an extremely risky business. There is thus a considerable mismatch between nearly all the literature on research resource allocation and that on decisions about investing in research in the risky environment in which this takes place*".

Representing uncertainty appropriately in agricultural research evaluation and priority setting is not straight forward. Various approaches are found in the literature to deal with this problem, each of them showing a varying degree of formal rigour and comprehensiveness. As a rough guide one can probably subsume these approaches into three categories:

- The first category may be labelled "formal risk analysis" and it is based on simulation and the definition of probability distributions of uncertain model variables.

- The second category is basically a deterministic approach where risk is addressed through sensitivity analysis of the uncertain parameters.

- In the third category, the incidence of risk is separated from the impact assessment by defining a "risk" objective on which research projects and programs are to be evaluated in conjunction with all other objectives.

Formal risk analysis usually treats risk in a quantitative manner either by applying analytical or numerical procedures. Only few examples are documented in the "agricultural research" literature. Because of the intractability of analytic procedures, most studies have dealt with studying the effect of uncertain variables on research outcome by using numerical procedures. In a pioneering work, SPROW (1967) introduced numerical simulation as a method for capturing the uncertainty in model variables and for estimating the joint effect of these variables on research impact with the use of subjectively elicited triangular probability distributions.[2]

SCOBIE and JACOBSEN (1992) have applied Sprow's approach for a research portfolio problem to analyse research priorities for the Australian Wool Research Council. They developed a Monte Carlo procedure to estimate the variance and covariance associated with research programs by simulating the economic benefits with each simulation based on a different set of randomly drawn parameters. Uncertainty was recognised for several different variables including yield increase, adoption rates, research and adoption lags as well as for the price elasticities of market demand and supply functions in an economic surplus model. They also included correlation among uncertain variables and estimated research benefit for alternative funding levels (ALSTON et al., 1996, p. 366). As cited in ANDERSON (1991, p. 109) a few other applications of simulation models have quantified the risk associated with returns from agricultural research such as the studies by FISHEL (1971), PARTON et al. (1984), DYER et al. (1984), and DYER and SCOBIE (1984).

There are a few more recent simulation studies with respect to agricultural research available. KAGUONGO et al. (1996) made an evaluation of the financial and economic impacts of different dairy technology changes on a whole farm basis in a Kenyan district covering the central highlands. The authors explicitly considered risk by making assumptions regarding dairy farmer's attitudes towards risk and by comparing the different dairy management strategies using stochastic dominance criteria. Uncertainty information was generated from a Monte Carlo computer simulation model called Technology Impact Evaluation Simulator (TIES). Stochastic variables were milk prices, project crops and cattle production levels and were derived from empirical probability distributions. BOSCH and SHABMAN (1990) developed a bio-economic simulation model which they later used to study the effects of alternative types of research information on the returns to oyster production. The model results provided an insight into the nature of research priorities that

[2] Sprow's approach to simulating random variates from triangular distributions is described in detail in ANDERSON et al. (1977, p. 267-270); and in ANDERSON and DILLON (1992, p. 46-51).

is appropriate for enhancing productivity in the oyster industry.

In their article on the value of economic research ZILBERMAN and HEIMAN (1997) describe some case studies that deal with impact assessment of social science research in agriculture where uncertainty has been acknowledged in one way or another. For example, ZILBERMAN et al. (1991) examined the benefits of agricultural economics research at Berkeley University resulting from their policy advise on the California's proposition to ban the use of chemical pesticide which has finally contributed to a disapproval of this proposition. The research benefits were assessed on the likely economic losses the proposition would have had, if implemented, on yield and output of several different crops due to reduced use of chemical pesticide. They simulated the outcome for several hundred scenarios in order to contribute to the high degree of variability in the estimates of the demand and supply functions. Expected impact results were then stated in terms of probability of exceeding or lying below certain benefit values.

An alternative approach to presenting uncertainty of policy impact estimates was used by SUNDING et al. (1997), quoted in ZILBERMAN and HEIMAN (1997, p. 19). SUNDING et al. (1997) considered the uncertainty surrounding the exact specification of modelling economic systems and used three different models to assess the impact of reducing water supplies to California agriculture associated with various versions of water reform legislation and water quality regulation for water supply in California.

There are a few other examples from the priority setting literature where uncertainty about parameter estimates in research impact assessment has been explicitly recognised. The Kenya Agricultural Research Institute (KARI) has undertaken a series of commodity research priority setting exercises, e.g., for the wheat (MILLS and KARANYA, 1997) and maize program (MILLS et al., 1995) in which yield increase estimates were represented as triangular probability distributions from which conditional expected yield increase and research success estimates were derived. But, instead of using simulation to draw samples from these distributions, MILLS et al. (1995) collapsed the probability distributions to single point estimates (expected yield increase and expected research success estimates), and thus undertook what may be described as a degenerate or deterministic analysis.

The most frequently used approach to risk is the use of sensitivity analysis where uncertainty about the precise value of some variables is taken into account. Most sensitivity analyses are treated as an extension to the main assessment analysis and are done in a second step after discussing evaluation assumptions and identifying the most critical and uncertain determinants of research impacts with modellers and experts. Almost every priority setting exercise documented in the literature has undertaken some sort of sensitivity analysis. Scoring models frequently use sensitivity analysis for different sets of objective weights while cost-benefit and economic surplus approaches usually test the sensitivity of research outcomes on different agricultural market prices, demand and supply elasticities, exogenous demand or supply growth or different social discount rates.

The third approach is to treat risk and uncertainty as a separate objective. Few examples of this type can be found in multi-criteria scoring models where risk is viewed from various different angles. In the context of priority setting risk may be considered as the effectiveness of research as a risk-reducing strategy that, along with other instruments, are aimed at stabilising agricultural markets, prices or farm income. Common risk related research objectives are national or regional food security, reduction in variability of farm output and income, or the distributional aspects of research concerning target groups who are especially exposed to environmental or economic risk. It is easy to recognise the different interpretations of risk compared to the two former approaches. While risk in simulation studies is handled by technical means in order to establish and reproduce stochastic variables or to test variables over certain value ranges, the treatment of risk as a separate objective is rather an arbitrary translation of risk into a research objective which has no direct connotation to the distinction between a deterministic and a stochastic system.

4.3.3 When Risk Matters in Agricultural Research

Why is it important to worry about risk and uncertainty in planning, evaluation and policy analysis? MORGAN and HENRION (1990, p. 43) summarise the cases where, on decision theoretic grounds, the explicit treatment of risk and uncertainty is important as:

- when one is performing an analysis in which decision makers' attitude toward risk is likely to be important, for example when people display significant risk aversion;
- when one is performing an analysis in which uncertain information from different sources must be combined. The precision of each source should help to determine its weighting in the combination;
- when a decision must be made about whether to invest resources to acquire additional information. In general the greater the uncertainty, the greater the expected value of additional information.

Risk neutrality is encountered very rarely in individual decision makers. Risk behaviour of decision makers have been studied quite well with respect to individual agricultural producers. It has been found that farmers especially small-scale farmers in developing countries are overwhelmingly risk averse and pursue several strategies to reduce risk by diversification of the farm enterprise (BINSWANGER, 1980). Most farmers adopt risk-reducing strategies involving such elements as flexibility, liquidity, diversification, caution in adopting new techniques and levels of input use that yield less than maximum expected returns. The decision making consequences are that risk averse decision makers are not "playing the average" (e.g., select a production portfolio that maximises expected farm gross margin) but follow more complex decision making rules including risk elements. Exceptions to risk aversion include occasional individuals (particularly extremely wealthy individuals) and approximate risk neutrality encountered when the decision making entity such as a government makes decision on behalf of many individuals (ANDERSON and DILLON, 1992, p. 4).

This latter case has led to the proposition that the appraisal of public investment activities such as research do not need to consider risk explicitly. A classic contribution to this subject was made by ARROW and LIND (1970) who put forward arguments that, in typical public investment decisions, the relevant criterion should be the expected net present values of returns on a public investment. The idea behind this is that government can effectively "pool risk into unimportance" through its large and diversified investment opportunities. So, if risk in public investments (e.g., agricultural research projects, programs, or whatever) is statistically independent and risk is borne by the public, then the total cost of risk bearing is unimportant, and for most practical purposes government should ignore risk in public project appraisal. If one accepts the Arror-Lind notion as a guideline for decision making in agricultural research, one would have not to worry about risk.

However, the relevance of the Arror-Lind argument for public agricultural research institutions may be questionable for three major reasons. The first is that the macro-level view may not be suitable for individual public research institutions. Although they receive large funds from the government and have limited financial autonomy, such institutions need to act on their own behalf in order to compete with other public institutions and to keep a good reputation. So, a risk averse research strategy with a largely diversified research portfolio may be called for in order to safeguard against major drawbacks. The second reason is that public agricultural research has become increasingly dependent on funds from external donors implying that risk of failure will not be fully borne by the local government but part of it must be taken by the institute itself. The third reason is that, from the society's point of view, government and public institutions should intervene to correct distortions and inefficiencies caused by the risk aversion behaviour of individuals. This would justify risky strategies of public institutions. The second issue in accounting for risk relates to the fact that different sources that contribute to uncertainty can interact together and possibly lead to unexpected results when research benefits are calculated in a deterministic way. In the most straight forward case – when uncertainty sources enter the analysis additively – summary measures of project performance such as NPV or CBR are a simple summation of the different sources of uncertainty; even if these happen to be statistically interdependent, the expected value is still readily calculated as a simple function of the relevant expected values of all components. On the other hand, when risks do not enter additively and linearly into the overall assessment, combining the expected values of the components may lead to biased estimates of the final expected values. In such cases, it may be necessary to explicitly take account of the different sources of uncertainty and the stochastic dependencies in order to produce unbiased estimates of the expected values.[3]

In addition to these standard decision-theoretic arguments, MORGAN and HENRION (1990, p. 43) have advanced several other reasons that might play an important role in real policy analysis. They argue that the treatment of uncertainty is important because it forces people to think about the full range of uncertainty associated with a problem. For example, instead of giving a single "best estimate" answer (e.g., the expected value of research benefits), the benefit measures may vary around a distribution of possible outcomes caused by the variation surrounding the underlying variables. Moreover, model building is necessarily an iterative process in which the analysis of sources of uncertainty can guide the design and refinement of a model to help to select the appropriate level of detail for each component. Finally, policy analysts may have the professional responsibility to present not just answers but also a clear and explicit statement of the implications and limitations of their work. Attempts to fully characterise and deal with the importance of associated uncertainties can help them to execute this responsibility better.

4.4 Generation of a Stochastic Framework for Estimating the Economic Gains from Dairy Research

In order to analyse risk and uncertainty it is necessary to turn the deterministic version of the economic surplus framework into a stochastic version. Stochasticity is introduced if one or more model variables of the economic surplus framework are represented as stochastic variables and are characterised through a probability distribution. For the majority of variables, there is no information available concerning the degree of uncertainty that would allow to determine a probability distribution. Prices and quantities for the dairy markets are derived from GIS as weighted single value estimates, research project costs are defined as some average values. In out example the stochastic problem is located in the components

[3] ANDERSON (1991, p. 115) comments that very little attention has been given to this subtle matter in the literature on project appraisal, and most of the available work has been rather abstract and of cautionary nature. This issue will be taken up once again in section 4.4.2 where the principle of induced correlation is introduced.

that determine the degree to which research is able to induce a shift in the supply schedule and determine the size of the economic research gains. More precisely, the stochastic nature is initiated by the net yield increase parameter which is expressed in terms of a triangular probability distribution function.

In the deterministic version, the probability of research success (RS = prob. ($YI \geq Yi_{th}$)) and the conditional net yield increase $YI = \mathrm{E}(YI \mid YI \geq Yi_{th})$ entered the economic surplus model as single values between 0 and 1 (RS), and as the expected value (YI). The approach used here to build a stochastic framework is to preserve and reproduce the randomness of the conditional net yield increase distribution using numerical simulation. To reproduce the randomness it is necessary to generate random variates $\tilde{Y}I$ by sampling from the conditional net yield increase distribution in a manner that reflects the distribution's shape. Then the sample values $\tilde{Y}I$ drawn from simulation are used instead of the expected value of the conditional yield increase $\mathrm{E}(YI \mid YI \geq YI_{th})$ by repeated runs of the economic surplus model, with each run based on another sample value. The final results are generated sample values for the net present value and cost-benefit ratio that form a probability distribution around them.[4]

4.4.1 Modelling Stochastic Variables Through Monte Carlo Simulation

Simulation and simulation modelling are frequently used terms to define various types of models and modelling techniques. In the light of this inconsistency it may be necessary to narrow down the meaning of simulation to the purpose of this study. PEGDEN et al. (1995) define simulation "*as the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/or evaluating various strategies for the operation of the system*". This is a general definition and one that is well suited to the use of simulation in economic-type applications. Simulation is often called a technique of last resort because it is used when the system to be modelled is too complex for analytical models to give adequate results. Simulation is used for modelling queuing-type systems, but it can be used whenever all or part of the system is stochastic in nature. In agriculture, simulation models are heavily applied to biological system analysis (e.g., crop simulation or environmental models) but show a somewhat lower profile in agricultural economics where they are helpful in business management, inventory

[4] Applying numerical simulation only for the probability distribution of the net yield increase conditional on exceeding the dissemination threshold value YI_{th} is one possibility for establishing a stochastic evaluation framework. It has been chosen because the resulting risk profiles are rather "naturally looking". Another possibility is to simulate from the complete triangular distribution which transforms both – the net yield increase and research success – into stochastic variables. Admittedly, the latter simulation procedure is preferable on theoretical grounds but would lead to "unnaturally looking" risk profiles. Both procedures yield different stochastic dominance test results.

control, investment appraisal and forecasting problems. In all these areas there is some uncertainty present in the system, which can be modelled by sampling from appropriate probability distributions. The term Monte Carlo simulation is often used for this type of simulation. LAW and KELTON (1991) define Monte Carlo simulation as " *a scheme employing random numbers, that is, U* (0,1) *random variates which is used for solving certain stochastic or deterministic problems where the passage of time plays no substantive role"*. The main interest here is the use of Monte Carlo sampling technique for stochastic problems.

Several techniques exist to sample from a distribution (FISHMAN, 1996; VOSE, 1996), but the most common is the "inverse transform" technique that can be applied easily to distributions with a finite value range (closed form distributions). The inverse transform concept uses the inverse of the cumulative distribution function (CDF) of the stochastic variable. Figure 4-3 provides a graphical representation of the relationship between the CDF $F(YI)$ the net yield increase and the inverse $G[F(YI)]$. To generate a random sample for this probability distribution, a random number (u) is generated between 0 and 1 from a uniform distribution function U (0,1). This value is then fed into the inverse CDF equation to determine the value YI to be generated. In practise, for some type of probability distributions, it is not possible to determine an equation for $G[F(YI)]$ in which case other techniques have to be employed for sampling from them. The statistical parameters, the probability density PDF and cumulative distribution function CDF of the triangular distribution can be calculated as follows (VOSE, 1996, p. 88):

(1) Mean: $$\frac{YI_l + YI_m + YI_h}{3}$$

(2) Variance: $$\frac{YI_l^2 + YI_m^2 + YI_h^2 - YI_l YI_m - YI_l YI_h - YI_m YI_h}{18}$$

(3) PDF: $$f(YI) = \frac{2(YI - YI_l)}{(YI_h - YI_l)(YI_m - YI_l)} \qquad \text{if } YI_l \le YI \le YI_m$$

$$f(YI) = \frac{2(YI_h - YI)}{(YI_h - YI_l)(YI_h - YI_m)} \qquad \text{if } YI_m \le YI \le YI_h$$

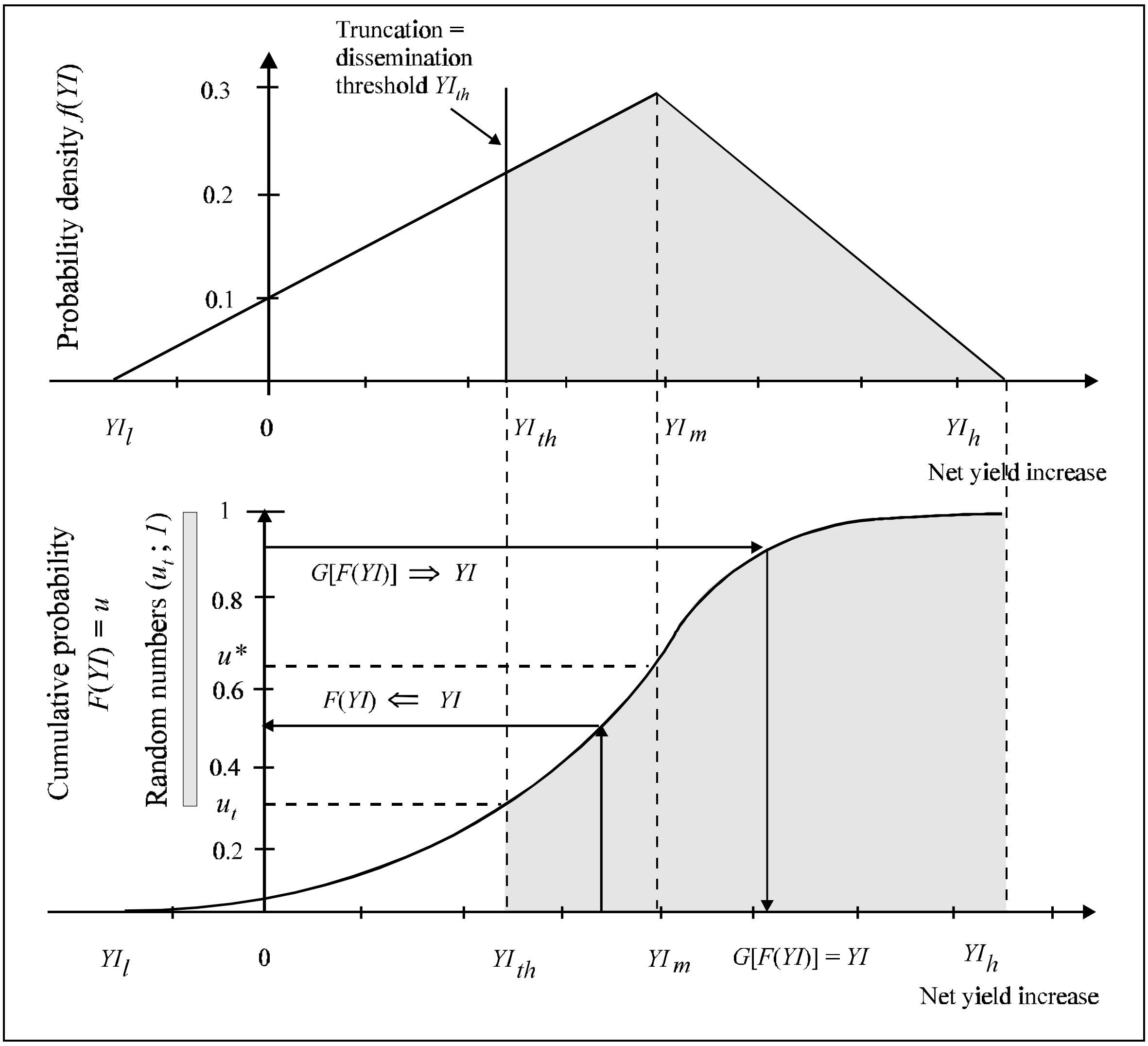
(4) CDF: $$F(YI) = 0 \qquad \text{if } YI < YI_l$$

$$F(YI) = \frac{(YI - YI_l)^2}{(YI_h - YI_l)(YI_m - YI_l)} \qquad \text{if } YI_l \le YI \le YI_m$$

$$F(YI) = 1 - \frac{(YI_h - YI)^2}{(YI_h - YI_l)(YI_h - YI_m)} \qquad \text{if } YI_m \leq YI \leq YI_h$$

$$F(YI) = 1 \qquad \text{if } YI_h < YI$$

Figure 4-3: Monte Carlo sampling from a triangular distribution representing net yield increase



Source: Modified, after VOSE (1996, p. 41)

Before the random variates *YI* can be derived from the random numbers *u* it is necessary to define two critical values. The first value is u^* which is the critical value of *u* that separates the two inverse transformation equations derived from the two different CDF equations above and below YI_m. The second value is u_t which defines the lower bound of the random numbers *u* leading to *YI* values that will lie above the threshold YI_{th} since by definition only those yield increase values are accounted for that lie above YI_{th}. In fact, random numbers *u* are only drawn between u_t and 1. Then u^* and u_t can be expressed as (MILLS et al., Appendix, p. 1995; DILLON and HARDAKER, 1977, p. 269):

(5) $$u^* = \frac{(YI_m - YI_l)}{(YI_h - YI_l)}$$

(6) $$u_t = \frac{(YI_t - YI_l)^2}{(YI_h - YI_l)(YI_m - YI_l)} \qquad \text{if } YI_m \leq YI_{th} \leq YI_h$$

(7) $$1 - \frac{(YI_h - YI_t)^2}{(YI_h - YI_l)(YI_h - YI_m)} \qquad \text{if } YI_l \leq = YI_{th} \leq YI_m$$

Depending on the magnitude of u or YI one of the following equations for the inverse CDF transformation must be used.

In case $u_t \leq u^*$ (or $YI_{th} \leq YI_m$) then:

(8) $$YI = YI_l + \sqrt{u(YI_h - YI_l)(YI_m - YI_l)} \qquad \text{if } u_t \leq u \leq u^*$$

$$YI = YI_h - \sqrt{1 - u(YI_h - YI_l)(YI_h - YI_m)} \qquad \text{if } u^* \leq u \leq 1$$

In case $u_t \geq u^*$ (or $YI_{th} \geq YI_m$) then:

(9) $$YI = YI_h - \sqrt{1 - u(YI_h - YI_l)(YI_h - YI_m)} \qquad \text{for all } u_t \leq u \leq 1$$

With this method it is possible to derive a sample distribution for yield increase in close accordance with the shaded area in Figure 4-3. However, the fit of the sample distribution very much depends on the quality of the random number generator in use regarding how well random numbers are evenly spread over the input domain $U(0,1)$. If random numbers are spread rather unevenly, then the values of the sampled distribution are spread unevenly as well, and this can often lead to sample values YI being underrepresented at the low probability tails of the distribution.

For this simulation study we used a stratified Monte Carlo approach known as Latin hypercube sampling (LHS). To generate n samples using LHS, each input distribution $U(0,1)$ is divided up into n equi-probable intervals (strata). Then a single value is sampled at random from within each of these intervals, according to the probability distribution and repeated n times. This produces a sample of n values that are more uniformly spread out and thus the sample from each input will represent the mean, variance, and other parameters of the distribution more accurately than with unstratified random sampling.[5]

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[5] For more information regarding LHS the interested reader is referred to MORGAN and HENRION (1990, p. 203 ff.), or VOSE (1996, p. 42 ff.). A VBA routine has been developed and is outlined in Appendix *C* to

4.4.2 Modelling Induced Correlation

The validity of any uncertainty analysis using simulation techniques is contingent on the validity of the inputs to the analysis. In the propagation of uncertainty, it is essential that the statistical distribution of input variables is properly specified, that the functional relationship of the input variables to the final output is correctly specified, and that any possible interaction or dependency among input variables is considered in the analysis. Dependencies among variables may occur when there is a logical relationship between two or more variables, e.g., interest rates statistically determine mortgage rate or investment costs, or where there is another external factor that is affecting both variables (e.g., the weather during a growing season of corn crops may affect the yields of wheat and barley in similar ways inducing a positive correlation between these two yield variables), or when the observed correlation has occurred purely by chance and no correlation actually exists.

Correlation in a stochastic research impact assessment model may be present at several locations for the reasons explained above. Numerous examples can be cited for correlation among stochastic variables caused by a common external factor e.g., when research impact is studied across various locations with similar or dissimilar biophysical production environment. The effect of a commodity research project on yield increase, costs reduction or adoption rates across the different locations should be positively correlated while the strength of correlation is influenced by the similarity of the locations. Another example could concern prices of regionally traded agricultural commodities where the degree of correlation between regional prices may be a function of market integration and distance of the different markets.

The second type of correlation is direct correlation which comes into play when one variable is a direct function of another model variable. For example, a direct correlation may be observed between potential yield increase and the level and speed of adoption since part of technology adoption is driven by the farmer's perception towards the improvement in cost saving or yield increase of the new technology compared to his current practise. A similar reasoning for assumed direct dependencies could be thought of between expected yield increase of a technology and research success or between costs and duration of a project and its expected research success. The effects of correlation on model results depend greatly on the relationship of the correlated components to the final output and on

implement the Latin hyper cube sampling scheme for a truncated triangular probability distribution on a MS-EXCEL spreadsheet.

their distributional shapes.[6] Some general guidelines can be made about the effect of correlation in common scenarios. In an additive scenario which assumes that the final output variable is defined as the sum of two or more stochastic input variables, the expectation of the sum is unaffected by correlation. It is readily apparent that correlation will affect the variance. Positive correlation inflates variance and the opposite will result from negative correlation. In the multiplicative case, both the mean and the variance of the final output are affected.

The failure to account for correlation – may it happen because it is simply assumed away or cannot be accommodated as in deterministic models – can lead to a serious bias in terms of expected value and variance of the research outcome.[7] Several methods exist that can incorporate such dependencies by inducing correlation among input variables in computer simulation analysis. One such approach is the "envelope method" described in VOSE (1996, p. 203 ff.) to generate linear or non-linear correlation between two or more random variables.[8] Other methods such as those described in BRANDES et al. (1980), and GOETZ (1993) have their shortcomings in that they depend on specific probability distributions (e.g., normal distribution), cannot handle more than two variables or fail to preserve the

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[6] Let us assume a simple bi-variate function $y = f(x_1,x_2)$ to analyse the effect of correlation between x_1 and x_2 on the mean and variance of y for the additive and multiplicative case (formulae are taken from SMITH et al., 1992, p. 469 ff.).

Additive case:

$$y = x_1 + x_2$$

$$E(y) = E(x_1) + E(x_2)$$

$$V(y) = V(x_1) + V(x_2) + 2\times \mathrm{cov}(x_1, x_2)$$

Multiplicative case:

$$y = x_1 \times x_2$$

$$E(y) = E(x_1) \times E(x_2) + \mathrm{cov}(x_1, x_2)$$

$$V(y) \approx V(x_1)\,[\overline{x_2}]^2 + V(x_2)\,[\overline{x_1}]^2 + 2 \times \mathrm{cov}(x_1, x_2)\,[\overline{x_1}]^2\,[\overline{x_2}]^2.$$

[7] SMITH et al. (1992) estimated the magnitude of potential biases resulting from neglecting correlated inputs for the sums and products of dependent inputs. For the additive case, they estimated a maximum bias of factor 2 for positive correlation. This implies that the output variance given positive correlation may be twice as much as the variance when correlation is totally ignored. An even more pronounced effect in terms of overstatement of the uncorrelated variance is seen for negative correlation (maximum factor 5).

In the multiplicative case, SMITH et al. (1992, p. 471 ff.) estimated a maximum bias of factor 5 for two lognormally distributed input variables when correlation is assumed away, and the bias in estimated variance will be approximately 20-fold.

[8] The envelope method is a technique of induced correlation that is based on the distinction between dependent and independent variables. Correlation is induced only on the dependent variables. The envelop method may be most suitable when correlation is of the direct form but inappropriate when correlation is caused by a common external factor and dependent and independent variables are hard to distinguish. Furthermore, the envelope technique is not very convenient for simulation purposes.

original distributional shape. There are mainly two approaches that are suitable for large and complex simulation models including multiple correlation. SCHEUER and STOLLER (1992) described an approach for generating multi-dimensional linearly (Pearson) correlated normal variates, which has found widespread use in simulation analysis. The second method has been developed by IMAN and CONOVER (1982) which describes dependencies in terms of rank-order (Spearman) correlation. Their approach can be referred to as the state of the art and has found widespread use in commercial simulation software.[9]

Accounting for dependencies can be problematic. It is noteworthy that simulation software for personal computers with the capability of inducing a correlation matrix on multivariate input vectors became readily available (e.g., @RISK and Crystal Ball) only within the past few years. Limitations in knowledge of dependencies is a more intractable problem. If one is simply seeking to determine the degree of correlation in modelling one could reproduce a correlation that has been observed in previous data. However, empirical estimates of correlation may be quite unstable when they are based on small sample sizes (SMITH et al. 1992, p. 468). Consequently, there can be considerably uncertainty in estimated dependencies.

Still more problematic are situations where dependencies are suspected but data to compute their magnitude are unavailable. An attempt to elicit estimates of correlation from experts may be difficult since evidence suggests that people are generally not very good at dealing with correlation structure and determining which level of correlation best represents their opinions (MORGAN and HENRION, 1990, p. 172-217). In practical modelling it may be best to try to avoid the problem of directly asking for quantitative assessment of correlation. Instead one could resort to short-cut procedures such as check lists by asking experts for a qualitative judgement about the direction and strength of correlation – e.g., whether correlation between input parameters is more or less non-existent, moderate or strong – and

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[9] The major advantage of the Iman and Conover's method is that:

- it is distribution free, thus it may be used with equal facility on all types of input distribution functions;
- it is relatively simple to use. No unusual mathematical techniques are required to implement the method; and
- it can be applied to any sampling scheme for which correlated input variables could logically be considered, while preserving the intend of the sampling scheme.

Analytical approaches and simulation software using the Scheuer and Stoller method (e.g., SIMSYS) make use of the Pearson coefficient of linear correlation. Commercially available simulation software which make use of Iman and Conover's method (e.g., @RISK and Crystal Ball) use the Spearman rank-order correlation coefficient. Because of the importance of the Iman and Conover's method and the rare documentation of the complete procedure in the literature, Appendix *C* provides a methodological summary and an outline of the source code of a VBA routine that allows the Iman and Conover's method to be implemented on a MS EXCEL spreadsheet.

then leave it to the modeller to determine an appropriate value for the correlation coefficient. Despite the unsolved problem of proper elicitation, such short-cut procedures to correlation estimation – even though the correct degree of correlation may not be very accurate – are justified when the evidence that correlation exists among several variables is striking. For this study a common need was felt to include correlation because all stochastic variables belong to the same research parameter and functional relationships between the variables – whether additive or multiplicative – were not clear prior to the analysis. For the simulation study ahead we used the rank-order correlation structure in Table 4-2 to account for the likely dependency between the regional specific net yield increases for the dairy research projects.

Table 4-2: Spearman rank-order correlation matrix for net yield increase across different agro-ecological zones

Agro-ecological zones for dairy production *	HR 1	HR 2	MR 1	MR 2	MR 3	LR 1
HR 1	**1**					
HR 2	**0.8**	**1**				
MR 1	**0.4**	**0.4**	**1**			
MR 2	**0.4**	**0.4**	**0.8**	**1**		
MR 3	**0.4**	**0.4**	**0.8**	**0.8**	**1**	
LR 1	**0**	**0**	**0.4**	**0.4**	**0.4**	**1**

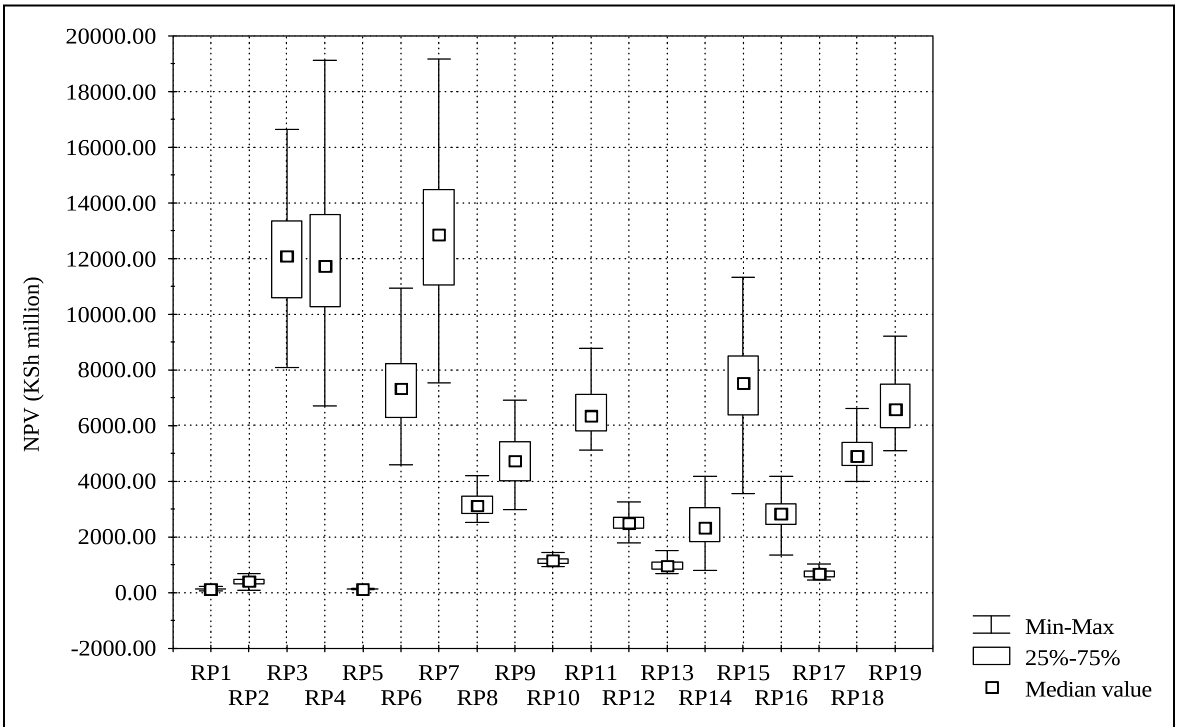
* HR 1 = high rainfall 1, HR 2 = high rainfall 2, MR 1 = medium rainfall 1, MR 2 = medium rainfall 2, MR 3 = medium rainfall 3, and LR 1 = low rainfall 1.

The correlation matrix in Table 4-2 is composed of subjective rank-order correlation values. The Kenyan dairy experts were not asked to specify correlation for yield increase across different zones because the model used in the workshop was deterministic. However, as a rough guideline to determining correlation coefficient values, it was assumed that agro-ecological zones within the same rainfall regime (e.g., HR 1 and HR 2) have a large overlap in production characteristics, hence induced positive correlation among yield increase for these zones was set rather high at $r = +0.8$. A somewhat lower positive correlation ($r = +0.4$) was assumed for neighbouring zones (e.g., HR 1 and MR 2), while no correlation was assumed between high rainfall (HR) and low rainfall (LR) zones.

4.5 Monte Carlo Simulation Results

Monte Carlo simulation was used to generate a sample of 200 observations drawn from the probability distributions of the net yield increase estimates. Each observation was then fed into the market model to calculate, after 200 runs, the final probability distributions for the net present values and cost-benefit ratio projects for each individual research project. Table 4-3 outlines some summary statistics and Figure 4-4 and 4-5 visualises these outcomes as box & whisker plots. Information on the shape and location of the distributions are indicated by minimum, maximum, median and 25% -75 % quartiles of the box & whisker plots. Two sets of Monte Carlo runs were conducted; one with correlated and the other with uncorrelated yield increase variates between the dairy market regions (see Table 4-2). The effects of including correlation on the outcome variable are such that correlation does not affect the mean of NPVs and CBRs but the standard deviation indicating a perfect additive function between the stochastic input parameters and the final NPVs. This is a quite surprising finding in view of the existence of the inter-linked spatial market model that combines yield increase estimates across the dairy regions.[10]

Figure 4-4: Distribution of net present value by project type from correlated yield increase (maximum, minimum, median, 25-75 % quartiles)



RP1, ..., RP19 define the 19 dairy research projects

[10] The purely additive nature of the regional market model might be due to the linear specification of the market functions. Non-linear functions, e.g., of the "Cobb-Douglas" function type, would presumably remove the additivity.

Table 4-3: Summary of the simulation results for 19 dairy research projects

Thrust	Project No.	Net present value (KSh million) (correlated yield increase)				Net present value (KSh million) (uncorrelated yield increase)			
		Mean	Standard deviation	Coefficient of variation (CV) in %	Shapiro-Wilk[11]	Mean	Standard deviation	Coefficient of variation (CV) in %	Shapiro-Wilk
FR	RP 1	127.56	30.89	24.22	0.965	127.54	25.26	19.81	0.968
FR	RP 2	395.86	117.04	29.57	0.980	395.94	83.25	21.03	0.977
FR	RP 3	12,022.28	1,845.21	15.35	0.971	12,024.95	1,200.99	9.99	0.985
FR	RP 4	12,021.78	2,479.60	20.63	0.975	12,027.21	1,847.28	15.36	0.973
FR	RP 5	125.44	6.91	5.51	0.924	125.44	6.91	5.51	0.924
FR	RP 6	7,340.22	1,350.30	18.40	0.969	7,337.30	959.44	13.08	0.971
FR	RP 7	12,790.13	2,390.16	18.69	0.976	12,793.50	1,642.29	12.84	0.984
FR	RP 8	3,186.38	418.30	13.13	0.934	3,187.05	272.77	8.56	0.978
FR	RP 9	4,745.87	941.28	19.83	0.961	4,745.68	899.19	18.95	0.962
AH	RP 10	1,149.29	111.61	9.71	0.958	1,150.69	75.24	6.54	0.978
AH	RP 11	6,498.20	846.97	13.03	0.940	6,493.94	539.86	8.31	0.953
AH	RP 12	2,511.19	305.14	12.15	0.977	2,511.82	205.95	8.20	0.982
AH	RP 13	973.73	178.47	18.33	0.956	972.18	99.39	10.22	0.985
AH	RP 14	2,403.58	804.79	33.48	0.962	2,405.43	526.06	21.87	0.962
AH	RP 15	7,496.12	1,461.27	19.49	0.983	7,500.73	1,023.78	13.65	0.973
BR	RP 16	2,829.69	537.73	19.00	0.984	2,831.11	349.78	12.35	0.981
BR	RP 17	679.30	136.24	20.06	0.951	679.23	136.11	20.04	0.951
SE	RP 18	5,007.16	590.32	11.79	0.949	5,007.78	376.73	7.52	0.984
SE	RP 19	6,774.55	971.12	14.33	0.936	6,771.02	613.17	9.06	0.955
		Cost-benefit ratio (correlated yield increase)				**Cost-benefit ratio (uncorrelated yield increase)**			
FR	RP 1	52.83	242.59	459.19	0.090	52.83	242.54	459.10	0.087
FR	RP 2	111.01	302.51	272.51	0.122	111.03	301.93	271.94	0.106
FR	RP 3	3697.61	567.49	15.35	0.971	3698.43	370.16	10.01	0.985
FR	RP 4	2963.79	613.81	20.71	0.975	2965.11	460.21	15.52	0.973
FR	RP 5	89.54	100.29	112.01	0.095	89.54	100.29	112.01	0.095
FR	RP 6	1126.62	441.98	39.23	0.450	1126.19	418.57	37.17	0.332
FR	RP 7	3295.32	615.33	18.67	0.976	3296.19	423.87	12.86	0.984
FR	RP 8	844.97	238.21	28.19	0.440	845.15	223.46	26.44	0.308
FR	RP 9	1071.25	320.28	29.90	0.673	1071.21	314.28	29.34	0.654
AH	RP 10	2095.32	231.52	11.05	0.931	2097.87	176.01	8.39	0.838
AH	RP 11	9209.38	1345.69	14.61	0.931	9203.34	975.25	10.60	0.830
AH	RP 12	8005.92	1117.32	13.96	0.932	8007.93	854.87	10.68	0.826
AH	RP 13	2205.07	423.84	19.22	0.978	2201.57	257.79	11.71	0.939
AH	RP 14	725.28	303.13	41.79	0.832	725.83	243.70	33.58	0.654
AH	RP 15	717.96	757.78	105.55	0.181	718.36	752.09	104.70	0.144
BR	RP 16	512.22	386.98	75.55	0.237	512.46	380.57	74.26	0.172
BR	RP 17	144.19	402.59	279.21	0.103	144.18	402.59	279.23	0.103
SE	RP 18	1632.58	217.00	13.29	0.909	1632.78	159.39	9.76	0.813
SE	RP 19	2203.78	320.69	14.55	0.938	2202.64	208.14	9.45	0.957

SD = standard deviation; CV in % = mean/standard deviation × 100; FR = Feed resources and utilisation; AH = animal health; BR = breeding and genetic resources; SE = socio-economics

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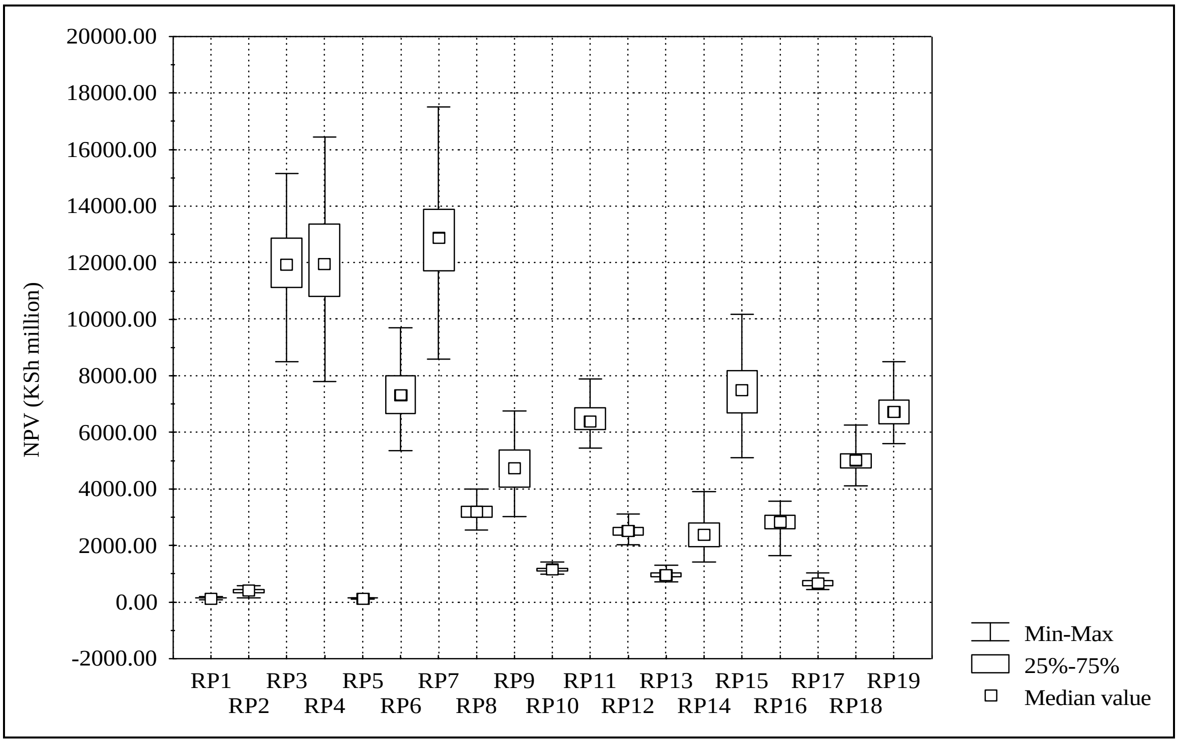
[11] The Shapiro-Wilk test statistic (W) computed as the ratio of the best estimator of the variance to the usual corrected sum of squares estimator of the variance. For sample sizes ≤ 2000 it produces a test statistic for the null hypothesis that input data values are a random sample from a normal distribution. The test statistic value must be $0 < W < 1$ with very small values leading to rejection of the null hypothesis.

On the other hand, standard deviations in the outcome distributions vary considerably. This is obvious because standard deviation increases steadily when correlation is shifted from -1 to +1 regardless of the functional relationship between input and output variables. Imposing positive correlation has increased the standard deviation significantly and, as the measure of the degree of uncertainty, is likely to have a significant influence on the project ranking based on stochastic dominance test results.

Figure 4-5: Distribution of net present value by project type from uncorrelated yield increase (maximum, minimum, median, 25-75 % quartiles)



RP1, ..., RP19 define the 19 dairy research projects

5 The Baseline Mathematical Programming Model

This chapter elaborates and illustrates the potential of mathematical programming models as a decision aid in priority setting by developing a simple baseline programming model to address the selection of research projects and the allocation of research resources across alternative research projects and research thrusts. The model is applied to the dairy research projects from the case study. The aim of the baseline model is to provide a direct alternative to scoring models and ranking tables by better incorporation of decision constraints, resource availability and multiple research objectives. As with scoring models, the baseline model incorporates multiple objectives and includes research benefits as deterministic values. In further sections of Chapter 5 modifications of the baseline model are developed to incorporate risks of project failure, the pursuit of different budgeting strategies and project interaction and selection problems. Some of these aspects are explicitly illustrated by examples and model runs.

The model structure is also fundamental to the development of extended mathematical programming models introduced in Chapter 7 where the analysis of risk and risk in combination with multiple objectives are the major focus.

5.1 Development of the Baseline Model

As a point of departure a simple mathematical programming model is developed in which research resources are allocated across alternative projects within a single research program under the assumption that each project is a discrete alternative having certain impacts and costs. Multiple research objectives can be accommodated through the specification of a composite objective function. The basic structure of the model is described in Figure 5-1. For simplicity, only two research objectives are considered, namely "efficiency" and "equity". So, the research benefit for a project is the discounted sum of the economic benefit over several years expressed by the present value. For the equity objective, research benefit may be stated as the discounted economic benefit for some particular regions or discounted consumer or producer surplus depending on the way equity is specified.

Because the time dimension is already incorporated into the coefficients of the objective function, the model can easily operate under a single-period specification, which keeps the model sufficiently simple. Simplicity is also preserved by defining discrete cost and impact values for each project instead of referring to a continuous research response function which eventually would introduce non-linearity into the model.

The decision activities of the model in Figure 5-1 are four research project alternatives P_1, ..., P_4. According to their predominant research topics, research projects can be grouped into broadly defined thrusts such as "breeding" and "animal feeding". All decision alternatives are coded in terms of [0; 1] integer variables (indicated by brackets), which means a project is a member [1] or non-member [0] of the solution set. Research domains or agro-ecological zones (AEZ 1 and AEZ 2) capture the spatial dimension of the research gains and also of the resources to be allocated.

Figure 5-1: Structure of a two-objective mathematical programming model for research project selection

Thrusts	Thrust 1 (e.g., breeding)		Thrust 2 (e.g., animal feeding)		Summation Variables				Objective Variables		Costs	Constraints	
Projects	**[P_1]**	**[P_2]**	**[P_3]**	**[P_4]**	**S_1**	**S_2**	**S_3**	**S_4**	**Z_1**	**Z_2**	**C**		
Definition of Constraints													
Resource availability	c_1	c_2	c_3	c_4								≤	R1
Budget share by thrust	c_1	c_2										≤ ≥	R2
Benefit share (objective 1 and AEZ 1)					1							≤ ≥	R3
Aggregation of objective function coefficients													
Contribution to objective 1 and AEZ 1	a_1^1	a_2^1	a_3^1	a_4^1	-1							=	0
Contribution to objective 1 and AEZ 2	a_1^2	a_2^2	a_3^2	a_4^2		-1						=	0
Contribution to objective 2 and AEZ 1	b_1^1	b_2^1	b_3^1	b_4^1			-1					=	0
Contribution to objective 2 and AEZ 2	b_1^2	b_2^2	b_3^2	b_4^2				-1				=	0
Summation of objective 1					1	1			-1			=	0
Summation of objective 2							1	1		-1		=	0
Summation of resource use (costs)	c_1	c_2	c_3	c_4							-1	=	0
Composite objective function									w_1	w_2	1	**maximise**	

Model elements:

→ Main decision variables (P_1, ..., P_4) representing discrete research projects;

→ Summation variables (S_1, ..., S_4; Z_1, Z_2) for aggregating research benefits by objective type;

→ Coefficients for resource use (c_1,...,c_4), e.g., costs, personnel for research projects P_1, ..., P_4;

→ Objective function coefficients (a_1^1, ..., a_4^2; b_1^1,..., b_4^2) for objective Z_1 and Z_2

→ Composite and additive objective function with objective weights (w_1; w_2) subject to maximisation

A variety of constraints is included such as constraints on available resources. For example, the constraint R1 may be the maximum program funding level, and c_1, ..., c_4 are the projects' individual budget requirements expressed in units of research expenditure. As a result, the total expenditures on all the research projects must be less than R1 which, when aggregated to the solution set, cannot exceed the maximum funding level. In the same manner maximum funding levels can be specified for certain thrusts (e.g., constraint R2) which may lead to the definition of upper and lower limits on the budget shares across thrusts (more on this issue can be found in later sections). Resource constraints may include other items than budget, for example, one could specify the availability of research facilities, personnel, transportation capacity, etc., on program or thrust level. Constraints can further be imposed on the allocation of the research benefits (e.g., constraint R3) across thrusts or AEZs while benefits may be the aggregate of all objectives or only a single objective. This way, it is possible to take into account distributional concerns with respect to the research benefits.

The coefficients a_1^1, ..., a_4^2 represent the contributions to research objective Z_1 and b_1^1, ..., b_4^2 the contributions to research objective Z_2 associated with each of the four research projects. As mentioned earlier, objective function coefficients may be discounted economic surplus estimates for efficiency and equity objective, but in fact could take any other dimension if the contributions to other objectives are measured in terms of e.g., labour hour/year, savings in foreign exchange expenditure, or subjective sustainability scores.

In this model, the objective variables Z_1 and Z_2 allow the summation of research benefits for a given research portfolio by any objective. Research benefits are then converted to objective functions values by defining weighting factors w_1 and w_2 on each research objective. The weighting factors w_1 and w_2 can range between 0 and 1 and they sum up to 1. Also, resource use coefficients need to be aggregated and incorporated into the objective function. This way, the composition of the objective function and, thus, the definition of the decision rule can be varied easily. For example, the model can be run by maximising a single research objective (either w_1 or w_2 take the value 0), a multiple research objective (w_1 and w_2 take positive values between 0 and 1) or by analysing the trade-offs between the two objectives by parametric variation of the objective weights between 0 and 1. Also, one could decide whether to include research costs or not.

5.2 Principles of Multi-Objective Analysis

Multi-objective programming (MOP), sometimes called "vector optimisation", tackles the simultaneous optimisation of several objectives subject to a set of constraints. Several variants of the basic MOP are available for obtaining a weighted " optimal solution or a set of feasible solutions that trade off the various objectives. So, MOP seeks to find the set of efficient solutions, also known as non-dominated or pareto optimal solutions. The elements of the efficient set are feasible solutions that can achieve the same or better performance for all objectives and strictly better for at least one objective (see Figure 5-3).

Essentially, there are two different approaches to generate or, at least, approximate the efficient set.[1] The first approach is the "weighting method" which combines all objectives into a single composite objective function by attaching objective weights *w* and then generating the efficient set through parametric variation of the weights (denoted as *a* in Figure 5-3). The second approach is the "constraint method" which involves optimisation of one objective and building the other objectives as constraints in the model. The efficient set is then generated by parametric variation of the right-hand side objective constraints. The variation of the constraints in Figure 5-3 is represented by the vertical shift of the constraint value for the objective *j* from $f_j(x^1)$ to $f_j(x^2)$. Thus, for a MOP problem with *q* objectives to be maximised, the weighting and the constraint method lead to the following mathematical programming problem which is outlined in Figure 5-2 (ROMERO and REHMAN, 1989, p. 71; 73).

Figure 5-2: Formulation of the "weighting" (1) and "constraint" (2) method in MOP for multiple (q) objectives [2]

(1) max. $Z(x) = w_1Z_1(x) + w_2Z_2(x) + ... + w_qZ_q(x)$ as objective function

subject to $x \varepsilon X$ and $w > 0$

(2) max. $Z_k(x)$ as objective function

subject to: $x \varepsilon X$ and $w > 0$, and

$Z_j(x) \leq \geq L_j \quad j = 1, 2, ..., k\text{-}1, k\text{+}1, ... , q$

where *w* = preference weights with Σw_j=1;

x = vector of decision alternatives;

$Z_k(x)$ = the objective to be maximised;

$Z_j(x)$ = the objective subject to constraint; and

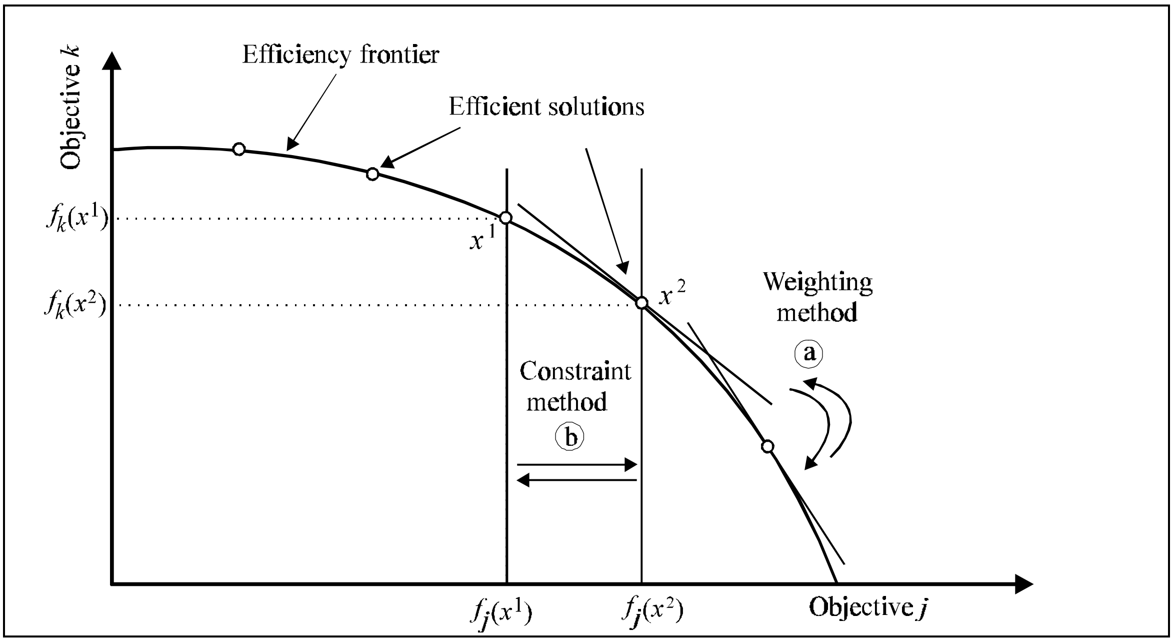
Lj = the right-hand side restriction on objective *j*.

[1] The true efficient set can be larger than the model set because not all efficient solutions may be detected. This mainly depends on the increments to which weights or constraints are changed. If increments are set too large, not all efficient solutions may be detected. To the best of my knowledge, there is no commercial MOP optimisation software available that directly searches for any efficient solution.

[2] Interpretation of the weights as measures for the relative importance or preferences of objectives is only valid if the decision maker's utility function is linear and additive as with the composite objective function (ROMERO and REHMAN, 1989).

Instead of generating a set of efficient solutions, one can alternatively define and apply a set of decision maker’s preferences or weights before optimisation so as to obtain a unique optimum solution. The advantage is that it avoids multiple model runs and can save much time; however this requires the decision makers to apply a particular set of preference weights. Furthermore, weights imposed prior to optimisation totally ignores insights into the trade-off between multiple objectives.

Figure 5-3: Trade-off curve between two conflicting objectives



The concept of efficiency frontier leads to another crucial concept in MOP: the value of the trade-off between two objectives. The trade-off between two objectives means the amount of achievement of one objective that must be sacrificed to gain a unitary increase in the other one. Thus, the trade-off T_{jk} between two efficient solutions x^1 and x^2 between the jth and kth objectives would be given by :

(1) $$T_{jk} = \frac{f_j(x^1) - f_j(x^2)}{f_k(x^1) - f_k(x^2)}$$

where $f_j(x)$ and $f_k(x)$ represent the two objective functions considered (ROMERO and REHMAN, 1989, p. 25). The trade-off values, besides being a good index for measuring the opportunity cost of one objective in terms of another under consideration, also plays a key role in interactive techniques. To help the decision makers choose the optimal solution from the efficient set generated by MOP, the model user can proceed with another programming approach called "compromise programming" developed by ZELENY (1973), or can employ "interactive techniques".[3] In principle, the "constraint" and "weighting" variants in MOP are both suitable for analysing multiple research objectives. Both MOP techniques generate the same set of efficient solutions as long as the objective space is strictly convex. But they significantly differ in their degree of quantification of the trade-offs and in the ease of presenting results to decision makers. The constraint method is better suited to situations where the number of objectives and solutions involved is considerable. The presentation of a large set of efficient solutions generated from varying constraints on target objective levels is much more comprehensive than solutions each generated with a different set of preference weights. The major disadvantage of the "constraint" variant is the possibility of unfeasible solutions when the constraint limit has been set too high, or constraints that are non-binding when the limit is set too low. Some stepwise testing is often necessary to identify the optimal range within which constraint values can vary.

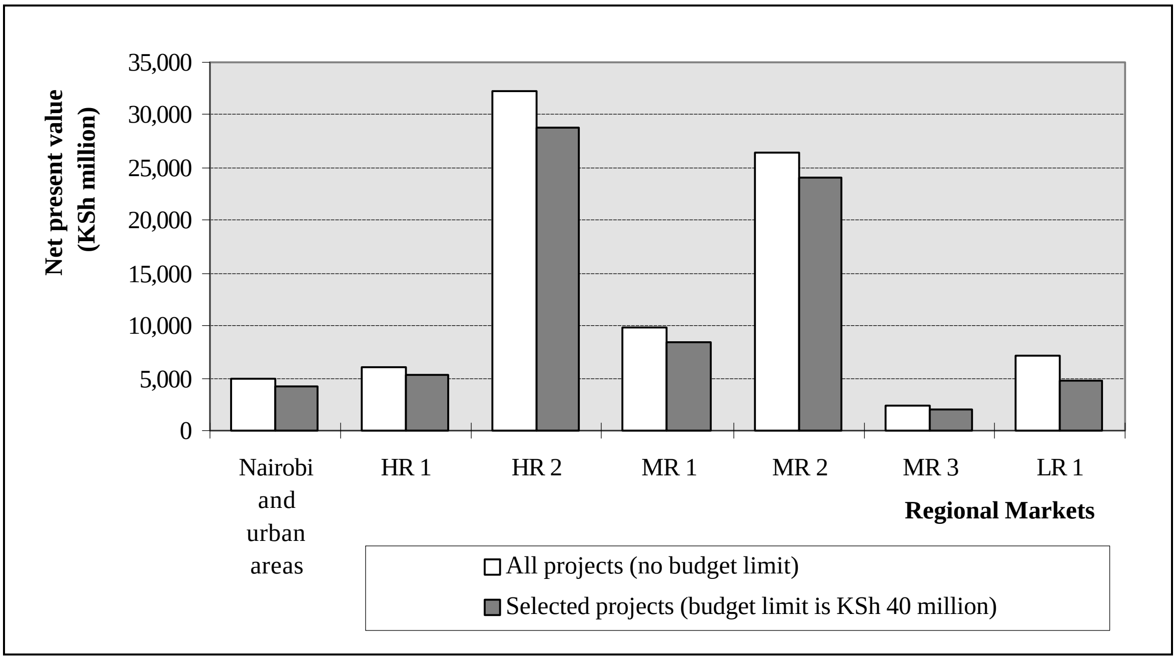
5.3 Application of a Multi-Objective Mathematical Programming Model

The following section describes the application of a mathematical programming model to the dairy case study. The analysis that follows focuses on an investigation into the simultaneous pursuit of efficiency and equity objectives. A MOP model of the "constraint" type is developed and solved by maximising efficiency (maximise the aggregate net present value) while various constraints are imposed on equity objective which is expressed as the spatial distribution of the research gains across the regional dairy markets in Kenya. Without explicit consideration of equity, the research gains would be very biased towards the high potential rural markets HR 2, MR 1 and MR 2 (around 70 per cent of the total net present value), and would disfavour the marginal rural markets MR 3 and LR 1 (they receive only around 10 per cent of the net present value). It can be readily studied from Figure 5-4 that the distributional bias is not much different if unlimited funds would allow the implementation of the complete set of projects, or only a limited set of projects if funds were limited to 40 million KSh.

Now let assume that the dairy research program would have to better reflect KARI's overall mandate to reduce poverty and generate agricultural income for disadvantaged people. Research managers of the dairy program would have to combine economic criteria, such as the economic performance of the research program, with the expected distributional effects the economic gains across the country in their decision process.

[3] The principle and practise of "compromise programming" are described in ROMERO and REHMAN (1989, p. 85-106); ROMERO et al. (1987).

Figure 5-4: Spatial distribution of the gains from dairy research across regional markets



HR 1 = high rainfall 1, HR 2 = high rainfall 2, MR 1 = medium rainfall 1, MR 2 = medium rainfall 2, MR 3 = medium rainfall 3, LR 1 = low rainfall 1.

The following analysis examines this problem by defining three hypothetical equity scenarios, where each scenario is based on a different set of constraints on the spatial distribution of the research gains.[4]

(1) In the first scenario, the target group of dairy research are the net consumers of milk living in the urban areas of Kenya. Since many of them are poor, dairy research should contribute to an increase in consumer surplus by provision of more milk coupled with a considerable reduction in the price of milk. Therefore, constraints are imposed on the minimum share of the research gains allocated to Nairobi and the urban centres in order to increase the initially low share of around 5.5 percent to, at least, 6 percent in a first step, and 7 per cent in a second step.

(2) The second scenario aims at securing minimum benefit shares to the Kenyan people in the less developed and drier parts of the country represented by the medium rainfall 3 and the low rainfall 1 zone. Constraints are imposed in order to lift the share of the total net present value from around 8 per cent to 10, 15 and 20 per cent.

[4] Chapter 7 presents two further approaches to equity. One approach classifies AEZs into two different sub-groups based on a land scarcity index, and a second approach subdivides consumers and producers of milk as the beneficiaries of the gains from dairy research.

(3) A similar equity scenario is pursued by imposing upper limits on the benefit share of the more favourable areas high rainfall 2 and medium rainfall 2 zones. These zones would normally capture more than two-third of the total benefits. The upper limits are set at a maximum share of 40, 50 and 60 per cent.

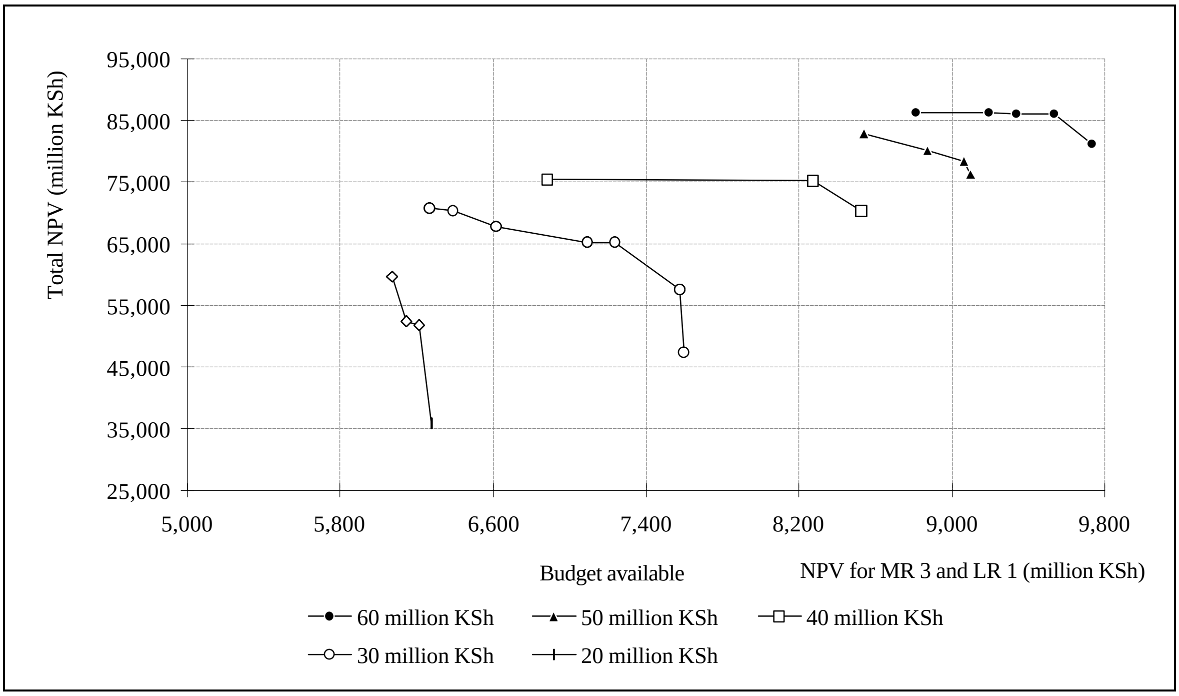
Model results for the different scenarios are presented in Table 5-1. All scenarios reveal that the composition of the research portfolios and, thus, the resulting spatial benefit distributions and total NPV are very sensitive to any constraint imposed on research gains, especially when the set of projects is rather small or when the budget is very limiting. The most sensitive to these constraints is scenario 1 within which benefit shares can vary only little, otherwise feasible research plans cannot be generated.

Table 5-1: Model results from three equity scenarios for the spatial distribution of the gains from dairy research

		Distribution of the net present values (NPV) by regional markets, including agro-ecological zones and urban areas (in KSh million)								Budget used
		Nairobi	HR 1	HR 2	MR 1	MR 2	MR 3	LR 1	Total	KSh million
Scenario 1: Minimum benefit share for Nairobi and urban areas (budget available: 40 million KSh)										
min. 6%	NPV	3,048	2,826	17,726	5,799	16,296	1,406	3,248	50,350	39.14
	%	6.05	5.61	35.21	11.52	32.37	2.79	6.45	100.00	
min. 7%	NPV	2,020	1,679	7,288	2,329	10,080	1,162	4,156	28,713	39.01
	%	7.03	5.85	25.38	8.11	35.10	4.05	14.48	100.00	
Scenario 2: Minimum benefit share for MR 3 and LR 1 (budget available: 40 million KSh)										
min. 10 %	NPV	4,051	5,105	27,420	7,859	22,506	2,067	6,207	75,216	38.93
	%	5.39	6.79	36.46	10.45	29.92	2.75	8.25	100.00	
min. 15 %	NPV	3,077	3,512	21,597	5,348	13,682	1,492	6,859	55,566	36.89
	%	5.54	6.32	38.87	9.63	24.62	2.69	12.34	100.00	
min. 20%	NPV	2,516	2,964	11,880	4,923	9,447	1,285	6,658	39,674	39.74
	%	6.34	7.47	29.94	12.41	23.81	3.24	16.78	100.00	
Scenario 3: Maximum benefit share for HR 2 and MR 2 (budget available: 40 million KSh)										
max. 60%	NPV	3,246	5,449	21,174	6,726	14,039	1,500	6,764	58,897	39.67
	%	5.51	9.25	35.95	11.42	23.84	2.55	11.48	100.00	
max. 50%	NPV	1,582	2,115	8,104	3,520	6,029	816	6,121	28,287	33.81
	%	5.59	7.48	28.65	12.45	21.31	2.89	21.64	100.00	
max. 40%	NPV	389	258	882	61	475	134	1,269	3,467	16.14
	%	11.21	7.45	25.45	1.75	13.69	3.85	36.60	100.00	

Based on these results, analysts are able to give helpful advise to decision makers, for example, that any compromise on a more balanced benefit distribution or the lobbying of target regions is inevitably associated with considerably losses in the overall research gains. The high opportunity costs for the sake of equity are apparent from Figures 5-5 and 5-6 that plot the results from the equity scenarios as trade-off curves. Figure 5-5 is based on model results for policy scenario 2 in which the minimum shares for MR 3 and LR 1 was increased continuously from a 10 per cent to a 20 per cent share, including 5 different funding levels for the research program. The strong trade-offs between efficiency and equity expressed in terms of total NPV versus NPV in the regions MR 3 and LR 1 suggests that the intended support for these regions may be very costly. Increasing research gains for these marginal regions is less harmful to the overall size of NPV when the available budget is high (indicated by the shape of the trade-off curve) but is considerable for low budget levels, e.g., at 30 million KSh.

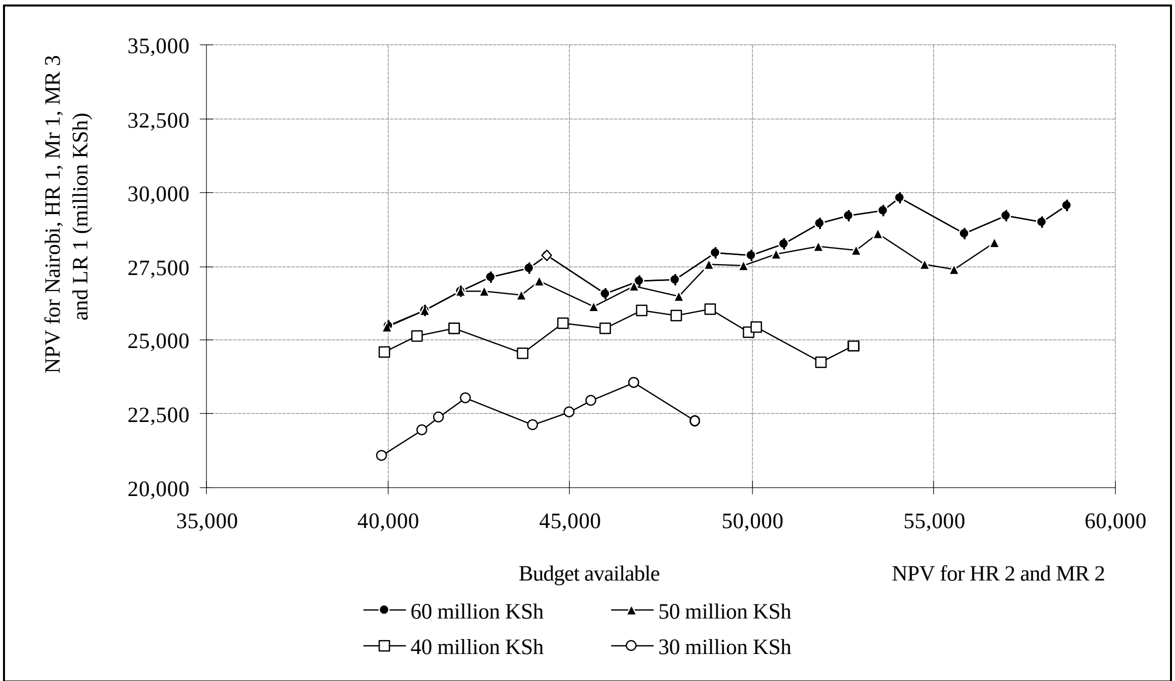
Figure 5-5: Trade-offs between efficiency and equity for equity scenario 2



MR 3 = medium rainfall 3, LR 1 = low rainfall 1 zone

In a similar fashion, model runs were conducted for scenario 3 under various budget constraints and continuous variation of the maximum benefit shares for HR 2 and MR 2. As shown in Figure 5-6 the trade-offs appear quite different because benefits for HR 2 and MR 2 are not plotted against total NPV but against the NPV for all other regions. It can be stated that trade-offs are even worse than for policy scenario 2 because reducing the maximum benefit share for HR 2 and MR 2 does not only reduce the proportion and absolute size of NPV for these regions, as intended, but also causes a reduction in the NPV for all other regions which is counter-productive and is against the initial policy intention to secure special support for these regions. To justify an equity policy which, of course, necessarily implies a trade-off between overall NPV and regional NPV, would require at least positive NPV effects for MR 3 and LR 1. This would manifest itself in Figure 5-6 as a convex trade-off curve between the two regional groups.

Figure 5-6: Trade-offs between efficiency and equity for equity scenario 3



Multi-objective analysis via the "constraint" type is a promising tool in decision analysis. It is easy to implement in a standard mathematical programming model and can be solved very fast. Furthermore, model results and their implications for efficiency and allocating research resources can be communicated easily. Probably the most important advantage is that using MOP via the "constraint" type does not require the elicitation of preference weights on objectives as required for the "weighting" method, which is always a source of confusion when analysts examine the validity of model results and propose modifications and sensitivity analyses.

5.4 Extensions of the Baseline Model

So far the simple baseline model developed above has given a first impression of the scope and possibility of mathematical programming models in priority setting. In reality such models should undergo further refinements in order to better reflect the specific circumstances of a research institution's planning effort. Therefore, the remaining sections of this chapter will focus on model extensions that have received widespread attention in the literature on research and development (R&D) project selection models. Four major extension types will be dealt with. These are:

- accounting for different budgeting strategies;
- restrictions on the level of research success;
- different types of research project interactions; and
- restrictions on research project selection.

The outline of the four extension types includes the description of their relevance for agricultural research institutions and also the possibilities of translating these extensions into the mathematical syntax of a mathematical programming model. To avoid unnecessarily lengthy details, an illustration is given only for the first extension type to show how different budgeting affects the composition of research portfolios.

5.4.1 Research Budgeting Strategies

An issue of theoretical and practical importance to R&D managers is the proper allocation of the institution's resources between periodic selection and budgeting of R&D projects and the implementation of these projects. One possibility is to consider previous allocations as the baseline and to restrict the attention of R&D managers to an examination of any subsequent deviations from this baseline. The advantage of this strategy, often called "incremental budgeting", is that it focuses managerial and analytical efforts on a few current decisions. A second possibility which is called "zero-base budgeting" is to ignore previous allocations and to re-examine all feasible alternatives at the start of each budget cycle (BLANNING, 1981, p. 547). Proponents of zero-base budgeting argue that all budgets should be based on a ‘"ground-up" or "zero-base" review of all alternative resource allocations for the sake of making the best possible use of available resources. Advocates of incremental budgeting argue that confining the institution to such a decision-making strategy can keep the costs devoted to implementation and the allocation process low. This is important, because resources allocated to decision making activities will not be available to fund projects (BLANNING, 1981, p. 548).

Agricultural research managers may find themselves in situations where they have to decide whether a set of new projects proposed in priority setting exercises with a complete different funding pattern than the base research program is acceptable or not. If the proposed projects are foreseen to replace some of the current projects, then the budget pattern for the whole program may change dramatically. According to the time schedule in program level priority setting, dramatic budget changes may even take place every 3 to 5 years. There are strong arguments that advocate some elements of incrementalism in research budgeting especially for agricultural research institutions. Many national research institutes have regional sub-centres whose mandate is often focused on one or a few research thrusts. To secure their operational base the funding by thrusts must be fairly consistent. Also, scientific and technical staff and many types of research equipment within research institutions are rather difficult to be relocated at short notice to other fields of research as a response to changed research budget. Below, a few examples are developed to show how elements of incrementalism can be incorporated into the baseline model. Admittedly, this is done in a rather simplistic fashion because; first, the baseline model has only one budgeting period; and second, only simple types of budget restriction were chosen. Multi-period models may require somewhat more effort but would still be confined to the same principle.

Table 5-2: Accounting for incremental budgeting in a mathematical programming tableau

	Initial budget proportions		Research projects				Aggregated costs		Right-hand side restrictions
	Thrust 1	Thrust 2	RP_1	RP_2	RP_3	RP_4	Thrust 1 C_1	Thrust 2 C_2	
	0.5	0.5							free
	15 mil. KSh	15 mil. KSh							free
			c_1	c_2			-1		= 0
					c_3	c_4		-1	= 0
							1	1	≤ 30 million. KSh
(a)							1		≥ 10 million KSh
							1		≤ 20 million KSh
								1	≥ 10 million KSh
(b)							0.4	-0.6	≤ 0
							-0.6	0.4	≤ 0

$RP_1, \ldots, RP_4$ denote research projects as decision alternatives;

C_1 and C_2 are summation variables for research costs; and

$c_1, \ldots, c_4$ are technical coefficients denoting project research costs.

For ease of exposition, the examples in Table 5-2 are based on a limited set of 4 research projects grouped into 2 different thrusts. The structure of the incremental budgeting formulation is as follows. A total budget of 30 million KSh is to be allocated among a set of research projects. The initial proportion of the budget is that each thrust receives 50 per cent, or in absolute terms: 15 million KSh. The total research costs $c_1, \ldots, c_2$ of a portfolio are then aggregated through the summation variables "C_1" and "C_2" to obtain the overall budget requirement for thrust 1 and thrust 2. Now, the first possibility to "incremental budgeting" is to define upper and/or lower bounds on the absolute budget by thrusts (option *a*) in which the generated portfolio can vary, or to impose a constraint on the budget proportions (option *b*). For example, option *a* confines the funding of thrust 1 to a minimum of 10 and a maximum of 20 million KSh, and thrust 2 must be funded with at least 10 million KSh. In option *b*, budgets shares are restricted to a range in which both thrusts can take up a share of only between 40 per cent and a maximum 60 per cent of the total budget.

Table 5-3: Model results from different budgeting restrictions

	Budget used by thrust										
	Thrust 1		Thrust 2		Thrust 3		Thrust 4		Total cost	Total NPV	Efficiency losses *
	KSh million	%	KSh million	%	KSh million	%	KSh million	%	KSh million	KSh million	KSh million
Option 1	27.70	*70.61*	5.37	*13.69*	0.00	*0.00*	6.16	*15.70*	39.23	77,550	/
Option 2	7.13	*29.14*	5.37	*21.95*	5.81	*23.75*	6.16	*25.16*	24.47	52,960	24,590
Option 3	17.87	*45.05*	15.64	*39.42*	0.00	*0.00*	6.16	*15.53*	39.66	74,865	2,685
Option 4	15.03	*39.75*	16.62	*43.96*	0.00	*0.00*	6.16	*16.29*	37.81	72,834	4,715
Option 5	11.19	*28.14*	16.62	*41.78*	5.81	*14.61*	6.16	*15.48*	39.79	72,478	5,072
Option 6	7.13	*19.96*	16.62	*46.53*	5.81	*16.27*	6.16	*17.24*	35.73	60,456	17,094
Option 7	19.53	*50.15*	13.25	*34.03*	0.00	*0.00*	6.16	*15.81*	38.93	75,177	2,373

Option 1: Zero-base budgeting, no restrictions on budget shares by thrusts;
Option 2: budget share for each thrust cannot exceed 30 per cent of total budget;
Option 3: maximum budget share of 50 per cent for thrust 1, free for all other thrusts;
Option 4: maximum budget share of 40 per cent for thrust 1, free for all other thrusts;
Option 5: maximum budget share of 30 per cent for thrust 1, free for all other thrusts;
Option 6: maximum budget share of 20 per cent for thrust 1, free for all other thrusts;
Option 7: Budget ratio of thrust 1 to thrust 2 can range from 50 / 50 per cent to 70 / 30 per cent.

NPV = net present value

* Efficiency losses are expressed in terms of loss in NPV of a restricted portfolio compared to a "zero-base budgeting" portfolio.

Table 5-3 presents results of model runs conducted for several values of budget restrictions. It is obvious that zero-base budgeting – in which budget shares can vary freely – results in the most effective allocation while incremental budgeting inevitably yields sub-optimal solutions.[5] The size of the efficiency losses mainly depends on the size of the increments to

[5] It should be noted here, that restricting the budget allocation has, among any other decision constraints and model modifications, probably the strongest effect on generating sub-optimal research portfolio.

allow the budget deviate from the initial "zero-base" pattern, and on the type of the restricted thrust. So, for example, restricting thrust 1 that contains many of the top- ranking projects is more harmful to the overall performance than doing the same for other thrusts. When adjusting models for different budgeting strategies, it should not be too difficult to ask research managers about how funds should be approximately allocated between thrusts given their knowledge about the type and location of research and the scientific staff employed in a commodity program.

5.4.2 Restrictions on the Level of Research Success

An agricultural research institution that depends on public funding and external donors must be concerned about its reputation as a successful entity and should therefore be cautious about pursuing a research strategy that embodies a high risk of project failure. Project failure can have a detrimental impact on the long-term survival of project manager's position, the operation of regional research centres or even of a whole research program. More seriously it can erode the credibility of the research institution with a long-lasting effect on the sustained acquisition of research funds from the government and international organisations. Although strategies that are aimed at maximising research benefits take into account research success indirectly – research success is one of the input parameters of the economic gains from research – it may be necessary to place stronger emphasis on research success issues than is usually done in the economic evaluation.

One may consider the need to incorporate research failure (or research success when looked from the other angle) in a mathematical programming model as a binding constraint in order to keep the probability of project failures low in the search for an appropriate research strategy. The major intention of this section is to elaborate ways of framing concern for project failure into model constraints and further to show how these constraints can be handled technically. No effort is made to conduct separate model runs under different research success constraints. A few examples of research success constraints in a R&D project selection model can be found in TAYLOR et al. (1982). Research success or failure can be accounted for in the process of generating research portfolios in various different ways. Below are a few alternative formulations of doing this that can make direct use of the research success information available from the case study. Possible constraint formulations are for example:

1. to impose a minimum probability level that all projects from a portfolio are successful in all agro-ecological zones;

Furthermore, it may happen that restrictions contradict each other when applied extensively, so that solving the model becomes impossible. Therefore, care is always needed when such constraints are used.

2. to impose a minimum probability level that all projects from a portfolio are successful for selected agro-ecological zones;
3. to impose a maximum probability level that all projects from a research portfolio fail completely in all or only selected agro-ecological zones;
4. to define a minimum number or proportion of projects that must have an average probability of research success of *x* per cent or above;
5. to impose a minimum level on the average success for a given research portfolio.

The development of model constraints is straight forward. The main target is to compile prior research success information by project type and by AEZ and further to apply elementary probability calculus for the transformation of this information into joint probability and average probability estimates. In Table 5-4 research success information is summarised and joint probabilities by project type and by AEZ are calculated from individual probability values. Joint probability by project type indicates the probability that a research project is successful (or not successful for the probability of research failure) in all AEZs. The joint probability by AEZ indicates the probability that for a given research portfolio all projects will succeed (fail) in a given AEZ. Apart from the joint probability, a second type of probability which is the average probability $\bar{p}_j$ can be simply calculated as the unweighted mean of a project's probability of success over all AEZs. With this information at hand it is possible to proceed with the mathematical formulation of the constraints which are shown in Table 5-5. Note that the joint probability is the product of the individual probabilities and therefore the constraint function is non-linear.

For example, constraint type 1 states that the probability that all projects will succeed must be greater than the probability p_{min}, or conversely, it also states that the probability of one or more failures should be equal to or less than 1 - p_{min} . Constraint 1 could be modified to include the exact probability of two or more failures, three or more failures, and in general *n* or more failures. The implementation is a more demanding task and is only practicable when the number of projects is small.[6] Constraint type 2 states that the probability that all projects will succeed for a given AEZ l_0 must be greater than the probability p_{min}. Constraint type 3 states that the probability of research failure including all projects must be smaller than $\tilde{p}_{max}$.

[6] This hinges mainly on the elicitation of the probability density and cumulative functions which becomes virtually impossible if the number of projects exceeds 3 or 4.

Table 5-4: Joint probability of research success by project type and agro-ecological zone

	Agro-ecological zones (AEZ)						Joint probabilities by project type	
	HR 1	HR 2	MR 1	MR 2	MR 3	LR 1		
	Individual probability of research success (RS)						Joint prob. of RS	Joint prob. of RF*
Project type	p_1	p_2	p_3	p_4	p_5	p_6	$\prod_{k=1}^{6} p_k$	$\prod_{k=1}^{6} \tilde{p}_k$
RP 1	0.8750	0.8750	0.8750	0.8750	0.8750	0.8750	0.4488	0.0000038
RP 2	0.9965	0.9965	0.9965	0.9965	0.9965	0.9965	0.9792	1.84E-15
RP 3	0.9462	0.8692	0.3214	0.8784	0.8856	/	0.2056	0.0000664
RP 4	/	0.9368	0.8199	0.8844	0.5404	/	0.3671	0.0006047
RP 5	0.9400	/	/	/	/	/	0.9400	0.0600000
RP 6	0.4450	0.8750	0.8497	0.8462	0.0333	/	0.0093	0.0015503
RP 7	1.0000	0.9592	1.0000	0.9688	/	/	0.9293	0.0000000
RP 8	0.3472	0.3472	0.4615	0.4615	0.4188	/	0.0108	0.0718220
RP 9	/	/	/	0.9110	0.8750	/	0.7971	0.0111250
RP 10	0.3063	0.3063	0.3063	0.3063	0.3063	0.3063	0.0008	0.1114372
RP 11	0.6094	0.6094	0.6094	0.6094	0.6094	0.6094	0.0512	0.0035513
RP 12	0.9688	0.9688	0.9688	0.9688	0.9688	0.9688	0.8268	0.0000000
RP 13	0.7750	0.7750	0.7750	0.7750	0.7750	0.7750	0.2167	0.0001297
RP 14	0.9550	0.9550	0.9550	0.9550	0.9550	0.9550	0.7586	0.0000000
RP 15	0.9861	0.9861	0.9861	0.9861	0.9861	0.9861	0.9194	0.0000000
RP 16	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000000
RP 17	/	/	/	/	/	0.7773	0.7773	0.2227000
RP 18	0.3767	0.3767	0.3767	0.3767	0.3767	0.3767	0.0029	0.0586385
RP 19	0.5037	0.5037	0.5037	0.5037	0.5037	0.5037	0.0163	0.0149440
	Joint probabilities by AEZ							
$\prod_{j=1}^{19} p_{jk}$	0.0030	0.0052	0.0023	0.0058	0.0001	0.0170	4.44E-16	/
$\prod_{j=1}^{19} \tilde{p}_k$	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	/	0.0000000

* RS denotes research success, and RF denotes research failure;

p_k ($\tilde{p}_k$) is the probability of RS (RF) for the *k*th AEZ with $\tilde{p}_k = 1 - p_k$;

n is the number of AEZs; and

m is the number of projects.

Constraint 4 states that a minimum number z of research projects must be members of the portfolio whose average probability of research success $\overline{p}_j$ must exceed that of a threshold probability value p_{min}.[7] Constraint type 5 would induce an average probability of research success for a portfolio that is at least equal to or larger than $\overline{p}_{min}$. The probability level $\overline{p}_{min}$ of constraint type 5 could be weighted by the NPV or the budget used in order to relate the incidence of project failure to the scale of the benefits and costs Of course, the list of proposed constraint formulations of research success is by far not exhaustive. Many other formulations could be thought of with a probably greater ease of comprehension but may have the disadvantage that they do not rely directly on the research success information that is readily available from the case study.

Table 5-5: Mathematical formulation of constraints on the probability of research success

Constraint number	Constraint formula	Functional type
1	$\prod_{k=1}^{n}(\prod_{j=1}^{m} X_j p_{jk}) \geq p_{min}$	non-linear
2	$(\prod_{j=1}^{m} X_j p_{jl_0}) \geq p_{min}$	non-linear
3	$\prod_{k=1}^{n}(\prod_{j=1}^{m} X_j \tilde{p}_{jk}) \leq \tilde{p}_{max}$	non-linear
4	$\min \{z \mid z \geq \sum_{j=J} X_j \}$, and $J = \{j\in \{1, ..., m\}: \overline{p}_j \geq p_{min}\}$	linear
5	$\frac{1}{m}\sum_{j=1}^{m} X_j \overline{p}_j \geq \overline{p}_{min}$	non-linear

p_{jk} $(\tilde{p}_{jk})$ denotes the probability of research success (failure) for the j th project and the k th AEZ;

X_j is the activity level of research project j (0 for non-member of the solution, and 1 for member of the solution set;

p_{min}, $\overline{p}_{min}$ and $\tilde{p}_{max}$ are the right-hand side probability values;

n is the number of AEZs, m is the number of research projects; and

l_0 is a selected AEZ

The constraint numbers refer to the listing of possible formulations presented earlier in section 5.3.2.

So far, the aspects of risks have been conceptualised as various constraints imposed on the probability of research failure. This approach to risk modelling has its advantage in an easy

[7] Constraint number 4 can be implemented in two steps. First, one needs to add a new row containing the [0; 1] technical coefficients of each project type with 0 denoting projects whose average probability of research success $\overline{p}_j$ is smaller than $\overline{p}_{min}$ and 1 denoting all other projects. In the second step, another row needs to be added including the minimum number of projects that take the value 1 as coefficient and the definition of z as the right-hand side value.

integration of readily available information of project risks into a mathematical programming syntax. However, many people may find this approach very technical treating risk in research in a rather artificial and little intuitive way. Therefore treating risk as constraints on research failure should be rather seen as a shortcut procedure in deterministic modelling while the following chapters introduce other and much better concepts that are based on stochastic modelling.

5.4.3 Research Project Interaction

A common assumption of a large number of project selection models in R&D that have utilised the concept of expected NPV of future profits attributable to projects is that the total NPV of a group or portfolio of projects can be obtained by summing the NPVs of projects in the portfolio. In this case projects may be said to have independent NPVs and, thus, the project selection model can be referred to as an "additive" model. Otherwise, the projects may be said to exhibit NPV interaction, or to be "interrelated". It is important to know that such interactions may be more common than realised and that they can have a significant effect on the NPV associated with a research portfolio. Ignoring such interaction may lead to sub-optimal portfolios and the allocation of research resources. One important motivation for examining project interaction is its frequent appearance in priority setting at the project level. Interactions between research activities are more likely to be present in the context of research projects at the smallest research unit than in the context of larger units such as research thrusts or programs.

One source of project interaction can be traced back to the transmission of technologies as research outcomes at the farm level where functional interactions exists within a set of sub-technologies that farmers use for the production of a commodity. These interactions affect the profitability of such sub-technologies and on aggregate the value of the research benefits. Interactions more often occur in livestock systems than in crop production systems due to complex bio-physiological and herd dynamics. A second source of project interactions can be attributed to scale effects of the use of resources e.g., number of researchers, number of field trials, and possibly the quality of the research outcome affecting both the cost and the benefit side. GEAR and COWIE (1980) have given a broad characterisation which distinguishes between interactions caused by internal and external factors.

According to GEAR and COWIE (1980, p. 739) projects may exhibit internal interactions “... *if the resource requirements and/or benefits of one project are thought to be significantly affected in magnitude and/or timing by the selection or rejection decisions relating to one or more of the other project in the set.*“ On the other hand, external interactions "... *arise* *over time from overall social and economic changes which have effects that cut across many, if not all, subsets of a project set*". The type of interaction considered in this section will be exclusively internal. In the R&D literature, internal interactions are further classified into three categories (BAKER and FREELAND, 1975; GEAR and COWIE, 1980): (1) cost or resource utilisation interaction; (2) outcome, probability, or technical interaction; and (3) benefit, payoff, or effect interaction.

Cost interaction may occur if the total costs of projects in the same set cannot be represented as the sum of the costs of the individual projects. This is often the case when projects share resources. For example some of the dairy projects may require the same piece of laboratory equipment (e.g., animal heath projects), or may use the same field trials (feeding projects). If the cost of these shared resources is included in each project requiring it, then the total cost of all projects is overstated, and the appropriate portion of the cost to be absorbed by each project cannot be determined unless the composition of the selected project is known.

Outcome interaction may occur if the probability of success of a given project depends on the outcome (success or failure) of one or more other projects; e.g., a project for the utilisation and conservation techniques of forage legumes may have no chance of success unless a prior project aimed at developing forage legume seeds is carried out and provides improved legume seeds. Outcome interaction may also occur in a hierarchical project network structure, where the highest level projects depend on the successful completion of lower level projects.

Benefit interaction among projects may exist if one project has an impact on the economic parameters, e.g., yield increase or adoption rate of one or more other projects. Therefore, project benefits are not additive and cannot be treated in an additive model as explained earlier. Depending on the direction of interaction projects may be complementary or competitive.

The treatment of project interactions in the project selection model faces several limitations. The first is that outcome interaction cannot be modelled as long as probability of research success between projects interact. However, later we will introduce the concept of mutually exclusive and inclusive projects which can be viewed as an extension of the concept of outcome interactions relating to the selection rather than the outcome of projects. The second limitation refers to benefit interactions that can be modelled only in a simplified way as present value (PV) interactions (FOX et al. 1984, p. 892). PV interactions is more or less a simplification that tries to count the net effect on PV or NPV directly rather than assuming that PV or NPV are endogenous variables determined by several input parameters one or more of which interact. Several R&D project selection models have approached the interaction problem that frequently embodies non-linearity with a non-linear integer model (see McBride and Yorkmark, 1980) while others have pursued a transformation into a binary linear model using one of the several methods proposed by Glover (1975), and Glover and Woolsey (1974).[8] Table 5-6 presents formulations of model constraints for all three interaction categories that are workable on a binary and linear programming model.

Table 5-6: Model constraints for project interaction

Interaction category		Decision variables			Right-hand side restriction
		RP1	RP2	RP3	
Cost interaction	Example 1[9]	1	1	-1	≤ 1
		1		-1	≥ 0
			1	-1	≥ 0
		c_1	c_2	$\pm c_3$	$\leq b$
Outcome interaction	Example 2[10]		1	-1	≥ 0
	Example 3		1	-1	≥ 0
		1		-1	≥ 0
Benefit interaction	Example 4	1	1	-1	≤ 1
		1		-1	≥ 0
			1	-1	≥ 0

RP1, ..., RP3 are research projects as decision variables, c_1, ..., c_3 are research project costs, and b is the available research budget.

In example 1, Table 5-6, the decision variables RP 1 and RP 2 represent two distinct projects. Variable RP 3 is used as an auxiliary variable to capture the joint cost $\pm c_3$ effect between c_1 and c_2. If RP 1 and RP 2 are able to share resources so that cost interaction tends towards cost reduction (complementary projects), then the value of c_3 is negative. On

[8] In some cases (Glover, 1975; Glover and Woolsey, 1974) these transformations correspond to the suggestion of grouping the projects into mutually exclusive and exhaustive portfolios that do not interact and treating these portfolios as "projects".

[9] Example 1 is composed of 3 adjunct constraints. The first constraint forces activity RP 3 into the solution set if RP 1 and RP 2 are both selected. Auxiliary constraints 2 and 3 prevent RP 3 from being in the solution set as long as RP 1 and RP 2 are not joint members of the solution set. The number of auxiliary constraints increases linearly with the number of joint projects.

[10] In examples 2 and 3 the selection of RP 3 is made dependent on the selection of RP 2. The major difference to the cost interaction example is that RP 3 is treated as optional and not mandatory if RP 1 and RP 2 are both in the solution set.

the contrary, if RP 1 and RP 2 are competitive with respect to cost[11], then c_3 takes a positive value. Examples 2 and 3 deal with outcome interactions between projects that are interlinked through research success. In example 2 variable RP 3 represents the dependent project whose project start and selection is made conditional on the successful implementation of RP 1 (example 2) or RP 1 and RP 2 in combination (example 3). In practise, RP 3 could be thought of as a large scale project which requires that RP 1 and/or RP 2, two pilot projects of the same research area, be first completed successfully.[12] Example 4 addresses the PV interaction type as a special case of benefit interaction between the two research projects RP 1 and RP 2. As with example 1, non-additive residuals are aggregated in RP 3 whose selection is a must if both projects are selected.

It can be shown that the technical side of modelling interaction presents no great difficulty. However, more demanding is the quantitative assessment of these interaction. Cost interaction is in general more accessible to quantification than benefit interaction. It may be suggested that the sharing of research equipment and other research inputs between projects, whose terms of references and structures are sufficiently known, can be readily ex-ante assessed by research experts. More difficulties arise in the direct assessment of the gains or losses in NPV from benefit interactions since the final NPV depends on various input parameters and the dynamic flow of benefits. Moreover, new difficulties arise when benefit interaction are of higher-order, which implies that more than two projects are involved. Another problem is the sometimes large number of interactions to be considered which would require adding a considerable number of model constraints and would make the optimisation of non-linear models almost intractable.

5.4.4 Restrictions on Project Selection

Several types of project interactions have been introduced. All have one thing in common, that is, interaction affects project performance either through cost, research success or benefit. Priority setting modelling often requires including, in a similar way, constraints regarding the composition of a research portfolio selection assuming that projects cannot be chosen independently. Here we try to elaborate possible reasons for the need to include constraints on project selections and furthermore to show how these constraints need to be formulated for a binary integer programming model. One reason for including constraints on

[11] E.g., RP1 and RP 2 are feeding projects that require field trials for testing a new grass variety. Around the research centre is a limited area that can be used as field trials only for one project. If both projects are to be selected field trials need to be moved to a more distant place from the centre thus causing some additional costs due to transportation and time.

[12] Observe that the correct interpretation of this example would have to recognise time aspects of project implementation. Nevertheless, for the sake of simplicity, the intention of the project selection model is not the explicit consideration or even optimisation of project scheduling.

project selection is that two or more projects can be "mutually exclusive". According to GITTINGER (1982, p. 377) mutually exclusive project analysis refers to projects or project designs that, by their very nature, are such that if one is chosen the other cannot be undertaken. For example, dairy research managers at KARI may be faced with the choice between two calf feeding projects that both address similar production constraints but it is too expensive to carry both of them out. This situation would be met in Table 5-7 by constraint type 1 and for the case of three projects by type 2.

Constraint types 1 and 2 are useful when a project can be planned in different variations e.g., in project design, in size or funding level. Then, every variation could be treated as a unique project and the selection of the best project in the portfolio should be left to optimisation. A variation of mutually exclusive projects is represented through constraint types 5 and 6. Here, mutually exclusivity is only partial between individual projects while other projects can be combined freely. For example, in constraint type 5 RP 2 and RP 3 are mutually exclusive – so choice must be made either between RP 2 or RP 3 while RP 1 can be combined either with RP 2 or with RP 3. This case may be applicable to a situation where, e.g., a large scale project on a new vaccine needs to be supplemented by a supporting project for testing appropriate vaccination scheme in different regions either in region *a* (RP 2) or in region *b* (RP 3).

Table 5-7: Model constraints for mutually exclusive and inclusive projects and other project selection constraints

Constraint number	Constraint type	Decision variables			Right-hand side
		RP 1	RP 2	RP 3	
1	2 mutually exclusive projects	1	1		≤ 1
2	3 mutually exclusive projects	1	1	1	≤ 1
3	2 joint projects	1	-1		= 0
4	3 joint projects	0.5	0.5	-1	= 0
5	3 partially mutually exclusive projects (option 1)	1	-1	-1	= 0
6	3 partially mutually exclusive projects (option 2)	1	-1	-1	≥ 0
7	Core projects	1			= 1

RP1, ..., RP3 represent research projects as decision variables.

Constraint type 6 extends this example by allowing RP 1 to be implemented with or without supporting projects. Opposite to mutually exclusive project selection are constraint types 3 and 4 which perceive projects as being adjunct, that means, they require each other for a successful completion of their intended objectives. There is great practical relevance for modelling adjunct project interdependency. Finally, constraint type 7 is aimed at identifying "core" projects that are of strategic importance so that they cannot be omitted from the research portfolio. Eventually, this constraint can be useful for including projects in the portfolio that would otherwise not be in the solution set, e.g., when a project was impossible to assess quantitatively in terms of NPV.

5.4.5 Concluding Remarks on Project Interaction and Project Selection

A decision analyst, perhaps an agricultural economist, whose duty is to work with the experts as a facilitator in elicitation process has to deal with project interaction and project selection issues in some way or another. An important experience from the dairy workshop at KARI in 1996 is that experts always tend to insist on a sufficient recognition of possible interactions – mostly on the benefit side – among the set of proposed research projects. The experts' opinion on a sound project evaluation may be largely influenced by the extent to which interaction effects from other projects are taken into account. Therefore, facilitators, decision analysts, or team leaders in a workshop need to be prepared to give assistance in approaching these project interaction problems. Otherwise research evaluation may take up too much time through endless discussions on evaluation details and may leave experts frustrated with the feeling that evaluation effort may completely fail.

Assistance must include the proposition of ways on how to disentangle and simplify the complexity of interaction, the identification of the main areas of interaction, their causes, the quantification and integration into the measurement. There is no unique answer to what the best procedures are. Nevertheless, as a rough guide, some basic suggestions may be worth pointing out. The easiest way to deal with interaction is to group interacting projects and treat them as a single project. This may be most suitable when several interaction types exist between two or more projects and their consequences on research impact are hard to quantify. Grouping projects has its disadvantage in that, if used intensively, experts may loose sight of the composition of the grouped projects and the complete set of individual projects. Furthermore, a serious problem emerges when adoption rates and yield increase values must be attached to the grouped project especially when these parameters differ markedly between the individual projects in the group.

Another unsolved problem is the determination of the proportion of research impact given to each individual project in a group. This becomes necessary when only one individual project out of the whole group must be chosen and experts want to have information on the likely performance of this project. In view of the shortcomings, grouping projects may be seen as a last resort, recommended only when all other possibilities are exhausted. More promising are those alternatives that have been introduced in the context of model constraint. It can be shown that technically, there is no great difficulty in incorporating various types of interactions as well as project selection constraints. What remains is the quantification of interaction with respect to performance. In most cases research experts would attach interaction to the input parameters such as adoption rates, yield increase or research success where, if the causes of interaction are transparent, the quantification may be straight forward. On the contrary, interaction between input parameters would be hard to incorporate in such a project selection model because it is operating on highly aggregate impact estimates. So, from the modelling perspective, the direct assessment of interaction on NPV (PV or PV interaction) would be preferable. Admittedly, this is a shortcoming of the model and further research effort is needed to elaborate possible alternatives.

6 A Stochastic Dominance Approach to Priority Setting

So far, decisions on research investments has been looked at in isolation from risk and uncertainty. Chapter 3 has outlined the concept of a deterministic economic surplus framework and provided detailed information on the evaluation results of the dairy research projects from the case study. Chapter 5 applied a deterministic mathematical programming model to analyse the effects of multiple research objectives and decision constraints. This deterministic view is surely a simplification of the reality since it presupposes that parameters for the gains from research are exactly predictable. However, a deterministic framework in which agricultural research planning is embedded considerably facilitates decision making. Assuming that research takes into account only efficiency as objective, research investments are economically worthwhile if they exhibit positive net present value or have a benefit- cost ratio greater than one. Decisions involving more than one investment alternative require to compare and rank investments according to their size of the economic gains, or to refer to optimisation of a research portfolio problem.

This chapter is the starting point for the stochastic analysis of decision problems in priority setting where the comparison of alternative research investments and research portfolio problems are extended to conditions of risk and uncertainty. Risk and uncertainty have been modelled and measured through Monte Carlo simulation and appear as probability distributions of the economic returns of the dairy research projects (see Chapter 4). As soon as research outcomes are stochastic and represented through a set of possible values and probability of occurrence, more advanced decision criteria as well as mathematical programming approaches must be employed.

The chapter gives a brief overview of decision criteria under uncertainty and introduces stochastic dominance (SD) as the most suitable decision concept for comparing and ranking risky research investments. In a next step, several stochastic dominance tests are applied to the 19 dairy research projects. Stochastic dominance results are compiled and visualised through the development of "risk ranking tables" that can establish an exact project ranking by including different preferences of decision makers towards risk. Subsequent sections in chapter 6 examine the question of the monetary value that can be attached to stochastic dominance relationships and perform a statistical analysis of the stochastic dominance results from the simulated data. This chapter concludes with the application of the "synthetic outranking approach" in combination with stochastic dominance analysis in order to address multi-objective decision problems under uncertainty.

6.1 Stochastic Dominance Concepts

Various decision criteria and rules under uncertainty exist, for example, "maximax", "maximin", "minimum regret" and many other criteria.[1] All these criteria are more or less short-cut criteria and open to criticism if for no other reason than the fact that all the information in the uncertainty outcome is not used and probabilities of states of nature are ignored (BAIRD, 1989, p. 142 ff.). Expected monetary value (EMV) is another commonly used criterion to value risky alternative but it ignores decision maker's preferences towards risk. The use of the EMV criterion assumes decision makers to be risk neutral and treats an average payoff of an uncertain outcome as being completely equivalent to a certain payoff of the same amount. The expected utility hypothesis (EU) is the basis for much of the theory of decision making under uncertainty. It states that choices made under uncertainty are affected by the decision maker's preferences and expectations, and it provides a general decision rule, which is the maximisation of the expected utility. EU requires that assumptions must be made on decision maker's preferences and the functional form of the utility function representing these preferences. In practise, it is an onerous task to derive decision makers' preferences and to choose the right utility function despite the fact that much research effort has gone into the development of preference and utility elicitation methods.[2]

Imprecision in the measurement of decision maker's preferences can be recognised or circumvented by using efficiency criteria rather than a single-valued utility function to order alternatives. There are two prominent efficiency criteria namely mean-variance approach (MV) – or as it is sometimes called, expected value-variance (EV) – and stochastic dominance. The most familiar efficiency criterion is the EV approach. Despite its widespread application, however, there are some important objections to the EV criterion. The most important is that the EV criterion is consistent with the expected utility hypothesis only when utility can be specified as a function of the mean and variance only. This occurs when outcomes are normally distributed, whatever the form of the utility function or, regardless of the distribution of outcomes, if a quadratic utility function is assumed (ANDERSON et al. 1977, p. 192-193). The development of the theory of stochastic dominance has provided an alternative approach to the analysis of uncertain prospects that

[1] An overview of decision criteria and their shortcomings can be found in MORGAN and HENRION (1990), BAIRD (1989), BRANDES and ODENING (1992), and several others monographs on investment and decision analysis.

[2] A methodological overview of utility and preference assessment procedures can be found in, e.g., KEENEY and RAIFFA (1993), and EISENFÜHR and WEBER (1993). KIMBROUGH and WEBER (1994) made an investigation of various different utility elicitation computer programs.

is, unlike EV and other moment-based methods, consistent with the theory of expected utility. SD does not require explicit knowledge of preferences and the functional form of the utility function but assumes only that a utility function must be one of the monotonically increasing von Neumann-Morgenstern type.[3] Also, SD is a distribution free concept, this means it can be applied regardless of the probability distribution function of the prospects to be compared. SD procedures reduce a choice set of alternative strategies through pairwise comparisons down to a smaller subset of all possible strategies which should include the strategy that maximises expected utility for a class of relevant risk preferences. The subset is referred to as efficient set and its members are risk efficient (or dominant) strategies for the preferences analysed.

Due to significant advantages over EV and other decision criteria for risky prospects, SD has experienced widespread use. Numerous examples of SD analysis exist in agriculture such as for fertiliser use (MAZID and BAILEY, 1992), bean production (BEZUNEH, 1992), the value of information for irrigation scheduling (BOSCH and EIDMANN, 1987), tillage systems in corn and soybean production (KLEMME, 1985) and winter-wheat-fallow (YIRIDOE et al., 1994), integrated pest management (GREENE et al., 1985), disaster assistance programs (KING and OAMEK, 1983), participation in farm commodity programs (KRAMER and POPE, 1981), smallholder dairying in Kenya (KAGUONGO et al., 1996), machinery selection (DANOK et al., 1980) and for many other topics.

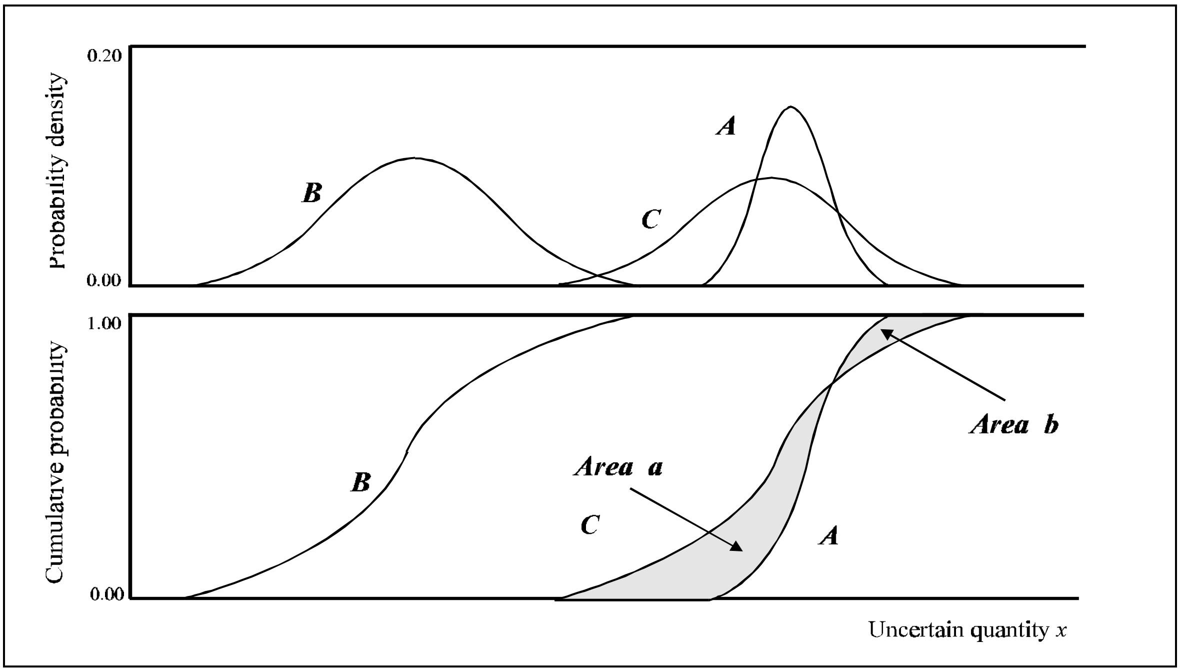
The stochastic dominance concept is not a single method but describes a set of different stochastic dominance criteria namely first-degree, second-degree, third-degree and stochastic dominance with respect to a function. The main difference is the underlying assumption regarding risk preferences. In the following section all these criteria are described in order of progressive strength of these risk preference assumptions.

First-degree (or first-order) stochastic dominance (FSD) places no restriction on decision makers' risk preferences. FSD needs to be stated in terms of the cumulative probability function and is a sufficient criterion to compare activities whose cumulative probabilities never cross. As outlined in Figure 6-1, activity *A* is preferred to activity *B* by FSD if the cumulative of *A* is less than or equal to the cumulative probability of *B* with the inequality holding for at least one level of return. Expressed in simpler words, this means that the cumulative of *A* must be equal or lie to the right of that of *B*, and at any value of the uncertain quantity *X*, the probability that *x* falls below a given value is lower for activity *A* than for activity *B*. FSD is perhaps not so important as an empirical matter since relatively

3 A general overview of the principles and procedures of stochastic dominance can be found in LEVY (1992), ANDERSON et al. (1977), and KING and ROBISON (1981).

few activities can be discriminated this way, e.g., only activity *A* from *B* but not activity *A* from *C*. Second-degree (or second-order) stochastic dominance (SSD) can be used to eliminate some further activities that cannot be eliminated by FSD if the cumulative distributions intersect. SSD embodies the restriction of only risk averse utility-maximising decision makers and may be represented through a concave utility function $U(x)$ with $U'(x) > 0$ and $U''(x) < 0$, that is, $U(x)$ has a positive but decreasing slope. Second-degree stcohastic dominance states that activity *A* is preferred to *C* by SSD if the CDF of *A* lies more to the right in terms of differences in area between the CDF curves cumulated from the lower values of the uncertain quantities. Such a SSD situation is depicted in Figure 6-1. Distribution *A* dominates distribution *C* by FSD until the point where both distributions intersect. Above the intersection distribution *C* dominates distribution *A* by FSD. To test for SSD it is necessary to compare area *a* with area *b*. In case that area *a* is greater than area *b* distribution *A* is dominant over *C* by SSD. A risk averse decision maker places greater weight on the superiority of a distribution at low level of the uncertain quantity *x* (the lower part of the CDF where distribution *A* is superior) than at high level of *x* (the upper part of the CDF where distribution *C* is superior) because of his decreasing marginal utility. If area *b* is greater than area *a*, SSD fail to discriminate distribution *A* from *C*, and more information about risk preferences, i.e., the approximate strength of risk aversion, is required.

Figure 6-1: Illustration of stochastic dominance criteria using probability density and cumulative probability functions



Source: Modified, after HARDAKER et al. (1997, p. 147)

In some applications FSD and SSD may not be able to discriminate sufficiently in the sense that too many alternative choices remain in the efficient set. The concept of third degree stochastic dominance (TSD) as explained in WHITEMORE (1970) and HAMMOND (1974) is an extension of FSD and SSD, and has the advantage that it can discriminate further from the SSD set of efficient activities. TSD depends on the same behavioural assumptions as FSD and SSD but imposes decreasing risk aversion as the new assumption about the underlying utility function.[4] The assumption of decreasing risk aversion is strongly intuitive since, as people become wealthier they tend to become decreasingly risk averse. Under TSD activity *A* dominates activity *B* if the area under the SSD cumulative never exceeds, and somewhere is less than the area under the SSD cumulative of activity *B*. Against this benefit TSD implies additional computational burden to derive the TSD set from the SSD set, and requires a general faith in the behavioural assumption of the underlying decreasing risk aversion. It has been shown that the discriminating power of TSD over SSD is often slight which makes TSD less useful than, for example, generalised stochastic dominance described next (ANDERSON, et al. 1977, p. 289).

The most flexible stochastic dominance rule is the stochastic dominance with respect to function (SDWRF), or sometimes referred to as generalised stochastic dominance (GSD), see for example MEYER (1977). GSD is an evaluative criterion which orders uncertain choices whose absolute risk aversion functions $r_a(x)$, known as the Pratt-Arrow risk aversion coefficient, lies within specific lower and upper bounds. The Pratt-Arrow absolute risk aversion function $r_a(x)$ is defined by the expression:

$$(1) \qquad r_a(x) = \frac{-u''(x)}{u'(x)}$$

where $u'(x)$ and $u''(x)$ are the first and the second derivatives of a von Neumann-Morgenstern utility function $u(x)$. In abstract terms, values of the absolute risk aversion coefficient are simply local measures of the degree of concavity or convexity of a utility function. As such they indicate the extent to which a decision maker is risk averse $r_a(x) > 0$, risk neutral $r_a(x)= 0$, or risk prone $r_a(x) < 0$. The absolute risk aversion function can be interpreted in terms of changes in marginal utility as the percent change in marginal utility per unit of outcome space as can be seen from the alternative definition of $r_a(x)$ as: [5]

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[4] The explanation of decreasing risk aversion follows later.

[5] Another measure is the relative risk aversion function $r_r(x)$ which is defined as $r_r(x) = r_a(x) \times x$. While $r_a(x)$ measures the percentage change of marginal utility per unit change of the outcome, $r_r(x)$ measures the same marginal utility per percent change of the outcome space. As such $r_r(x)$ is the elasticity of the marginal utility and it is unitless. Some further details on the $r_r(x)$ can be found in KEENEY and RAIFFA (1993).

(2) $$r_a(x) = -\frac{d}{dx} \log u' \text{ or } -\frac{(du'/u')}{dx}$$

Therefore, $r_a(x)$ has associated with it a unit – the reciprocal of the unit in which the outcome value is defined. Suppose the outcome is measured in dollars and $r_a(x)$ has a constant value of 0.0001 (slightly risk averse), this indicates that near the outcome level at which the elicitation was made, the decision maker's marginal utility is dropping at a rate of 0.01 per cent per dollar change in income. Similarly, if $r_a(x)$ has a value of -0.0005 (risk prone), this implies that around the outcome level of x the marginal utility is rising at a level of 0.05 per cent per dollar change in income. The major advantage of GSD is that it imposes no restrictions on the width and shape of the relevant risk interval since lower and upper bounds of the interval can be placed anywhere in the risk aversion space. In this respect, FSD and SSD can then be viewed as special cases of this more general criterion. So, FSD tests could be substituted by GSD tests with $r_a(x)$ bounds set between [-∞; +∞] which implies that no restriction is placed on the risk aversion function. On the other hand, GSD tests with a $r_a(x)$ range between [0; +∞] would be equivalent to a SSD test.[6]

The absolute risk aversion function $r_a(x)$ is a local measure of risk preferences and may change – depending on the utility function – over the level of x. Then, if $dr_a(x)(dx) < 0$ we have a decreasing absolute risk aversion (DARA). Similarly, if $dr_a(x)(dx) = 0$ we have a constant absolute risk aversion (CARA); and if $dr_a(x)(dx) > 0$ the risk aversion is increasing (IARA). Most known SD computer programs assume CARA properties of the utility function. Another characteristic of $r_a(x)$ is that it is invariant to linear transformations of u but not invariant to arbitrary re-scaling of the outcome variable x. The effects of this misunderstanding has led to ambiguity in classifying attitudes such as strongly, moderately, or slightly risk averse for values of the risk aversion function. Very often, risk aversion functions and the corresponding interpretation of the risk intervals were taken from other studies ignoring the different outcome scale (see Table 6-2 for an overview of used risk aversion intervals). At worst, this can lead to inaccurate ranking of action choices. But RASKIN and COCHRAN (1986) have shown that re-scaling is rather trivial.[7]

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[6] All stochastic dominance techniques discussed so far require that a consensus on the ranking of actions choices be reached before any alternative is rejected from the efficient set. CHOCHRAN et al. (1985) developed a new technique called "convex set stochastic dominance" which can be used to discriminate further between the expected utility of the action choices without imposing additional restrictions on the utility function. It accomplishes this by relaxing the requirement that a consensus of all decision makers is necessary to reject an action choice as being risk inefficient.

[7] For a transformation of the scale of x such as $w = x / c$, where c is a constant, the adjusted risk aversion coefficient $r_a(w)$ is then adjusted by $c \times r_a(x)$. In other words. if the outcome scale is contracted by the factor c, then the value of $r_a(x)$ must be multiplied by the same factor. On the other hand $r_a(x)$ is unaltered by an additive shift (or translation) of the scale of x. If for example $w = x + c$, where c is a constant, then the

Table 6-1: Mathematical formulation of different stochastic dominance concepts

Stochastic dominance criteria	Risk preference interval		Mathematical description (Distribution F dominates G)
First-degree stochastic dominance	$-\infty < \frac{U''(x)}{U'(x)} < \infty$	From risk averse to risk prone	$G(x) - F(x) \geq 0$
Second-degree stochastic dominance	$0 < \frac{-U''(x)}{U'(x)} < \infty$	Risk averse	$\int_0^x [G(x) - F(x)]\, dx \geq 0$
Third-degree stochastic dominance	$0 < \frac{-U''(x)}{U'(x)} < \infty$; $U'''(x) < 0$	Risk averse	Let $\int_0^x [G(x)]\, dx = G_1(x)$ and $\int_0^x [F(x)]\, dx = F_1(x)$ then $\int_0^x [G_1(x)]\, dx \geq \int_0^x [F_1(x)]\, dx$
Generalised stochastic dominance (Stochastic dominance with respect to a function)	Flexible $r_1(x) < \frac{-U''(x)}{U'(x)} < r_2(x)$ $r_1(x)$, $r_2(x)$ specified by researcher*	Range specified by researcher	$\int_0^x [G(x) - F(x)]\, U'(x)\, dx \geq 0$ subject to: $r_1(x) < \frac{-U''(x)}{U'(x)} < r_2(x) \quad \forall x \in [0;1]$ and $U(x)$ is a utility function

* $r_1(x)$ and $r_2(x)$ are Pratt-Arrow absolute risk aversion coefficients

Source: Compiled from WOLFSTETTER (1996); GOH et al. (1989, p. 176)

A few problems are encountered when ordering alternatives using stochastic dominance tests. The first problem relates to the well known empirical inadequacy arising because the application of SD rules are subject to sampling errors inherent in the sampling for the empirical probability density and cumulative functions. Like any statistical analysis, the SD rules are subject to type I or type II errors. LEVY and KROLL (1980), POPE and ZIEMER (1984), STEIN et al. (1987) and others use simulation techniques to determine the probability of correctly ascertaining correct dominance relationships. Many of these studies show that empirical applications of SD have very low power, indicated by high proportion of type I and II errors (NELSON and POPE 1991). Much of the problem results from the variability in the tail observations of the CDF. BEN-HORIM (1990) suggests that truncating the CDFs can circumvent this problem without great loss of accuracy in the distributions to be compared. Some SD computer programs offer so called quasi-first (q-FSD) and quasi-second-degree (q-SSD) stochastic dominance options with truncated left tails of the CDF. This way, a distribution *A* can be discriminated against another distribution *B* by FSD even

adjusted $r_a(w)$ is simply the original $r_a(x)$.

though a single or a few outlying sample values in the tail regions would cause an intersect of the CDFs (see for example, GOH et al. (1989, p. 176) in the description of the "generalised stochastic dominance program"). A second problem exists with GSD that is the specification of the lower and upper bounds of the absolute risk aversion function $r_a(x)$. From Table 6-2 it can be seen that many studies reported in the literature use risk preference intervals while only a few made an effort to empirically assess the range of $r(x)$.

Table 6-2: Summary of commonly used risk version coefficients in empirical studies

	Study	Year	Almost risk neutral	Strongly risk averse	Outcome variable	Source of $r_a(x)$
1)	Danok, McCarl and White	1980	/	0.1	Annual farm income	Assumed
2)	Kramer and Pope	1981	.000 to .00125	.02 to .03	Annual farm income	Assumed based on C.E.
3)	King and Robison	1981	-.0001 to .0001	.001	Annual income	Elicited (IPM)
4)	Wilson and Eidman	1983	-.0001 to .0001	.0002 to .001	After-tax annual farm income	Elicited
5)	King and Oamek	1983	-.00001 to .00001	.00005 to .0001	Annual farm income	Elicited (IPM
6)	King and Lybecker	1983	-.0001 to .0001	.0003 to .0006	Annual income from 1,000 cwt dry beans	Assumed
7)	Love and Robison	1984	-.00001 to .0002	.0025 to ∞	After-tax annual income	Elicited
8)	Rister, Skees, and Black	1984	-.00001 to .00001	.00004 to .00008	Annual return to grain storage	Assumed based on C.E.
9	Zacharias and Grube	1984	-.0000001 to .000001	.000042 to .0035	Annual farm income	Assumed threshold
10)	Tauer	1985		.0002 to .0003	$100,000 farm purchase	Assumed based on King and Robison
11)	Cochran	1985	-.0001 to .0001	.001	Annual farm income	Assumed based on Love and Robison; Cochran, Robison, and Lodwick
12)	Greene et al.	1985	.0 to .00125	.005 to .0075	Annual farm income	Assumed
13)	Tauer	1986	-.0001 to .001	.001 to ∞	Annual farm income	Elicited
14)	Bosch and Eidman	1987	-.00005 to .0001	.0003 to .0015	Value of information	Assumed based on Lin, Dean, and Moore; Knowles; Wilson
15)	Yiridoe et al.	1994		.001	Crop net returns	Assumed based on C.E.

I.P.M. = Interval preference measurement

C.E.= Certainty equivalent

Source: Compiled from BOSCH and EIDMAN (1987); RASKIN and COCHRAN (1986); and YIRIDOE et al. (1994)

Both cases seem to have major shortcomings: one is the already mentioned scale sensitivity of $r_a(x)$ when risk intervals are taken from literature, and the other is the time requirement for an empirical elicitation. For these reasons KING and ROBISON (1981) have developed an operational procedure namely "interval preference measurement technique" for a simplified elicitation of lower and upper bounds of a risk interval. Another possibility is the use of the McCarl and Bessler's non-negative certainty equivalent technique as cited in YIRIDOE et al. (1994) to set approximate upper bounds on the risk range $r_a(x)$. This bound is equivalent to twice the inverse of the coefficient of variation (CV) divided by the standard deviation (SD) of the empirical distributions expressed mathematically as $r_{\text{upper}} = 2/(CV \times SD)$. However, unlike other tests GSD requires the analysts to gain a great deal of experience through repeated test runs before risk bounds are set at the right scale and also require much time until dominance results are analysed and complete rankings are established.

6.2 Stochastic Dominance Results and Risk Ranking Tables for the Dairy Program

Stochastic dominance analysis was carried out based on the cumulative distributions of net present values and cost-benefit ratios calculated from the simulation data set with induced correlation. Stochastic dominance analysis is an analytically demanding task especially when the set of projects is rather large because it requires the comparison of every possible project pair. Additionally, large project sets are often faced with many different stochastic dominance relationships that cannot be explored by a single test program. In our example three different computer programs are employed, namely, the "meyerroot" program by MCCARL (1989), the "riskroot" program by MCCARL (1988) and the "generalised stochastic dominance program" (GSDP) developed by GOH et al. (1989). All these programs operate on MS-DOS level. In the first step, the "meyerroot" program is employed to discriminate projects by FSD and SSD criteria. FSD are then dropped since they have already established clear order regardless of the attitudes towards risk.. In the second step, all unclear cases (non-FSD) are examined by calculating the break-even risk aversion coefficient (B-RAC) for any project pair which is the critical value of $r_a(x)$ such that on each side (below and above) of $r_a(x)$ the dominance between a pair of research projects is reversed. To identify B-RACs, the "riskroot" program is used which finds these critical $r_a(x)$ values. At the end of second step, stochastic dominance relationships are unambiguously established either in terms of FSD or B-RAC values. The final results of the pairwise comparisons of all 19 research projects are presented in Table 6-3 and Table 6-4. Screened risk intervals for $r_a(x)$ were set to range between -0.03 and +0.03 which is slightly larger than the range that would have resulted from the McCarl and Bessler's non-negative certainty equivalent.

Table 6-3: Pairwise comparison matrix to investigate first-degree stochastic dominance and break-even risk aversion coefficients (B-RAC) for the dairy research projects ranked by net present value [a), b)]

RP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	- -																		
2	D	- -																	
3	D	D	- -																
4	D	D	-.0000 00399	- -															
5	(.00488)	(D)	(D)	(D)	- -														
6	D	D	(D)	(D)	D	- -													
7	D	D	.00084 3435	D	D	D	- -												
8	D	D	(D)	(D)	D	(D)	(D)	- -											
9	D	D	(D)	(D)	D	(D)	(D)	D	- -										
10	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	- -									
11	D	D	(D)	(D)	D	(.00261 056)	(D)	D	D	D	- -								
12	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	D	(D)	- -							
13	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	-.0179 5886	(D)	(D)	- -						
14	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	.01429 0395)	(D)	-.0003 91506	D	- -					
15	D	D	(D)	(D)	D	.00070 7822	(D)	D	D	D	.00140 7650)	D	D	D	- -				
16	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	D	(D)	.00345 0016	D	(-.0060 91744	(D)	- -			
17	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	- -		
18	D	D	(D)	(D)	D	(D)	(D)	D	(-.0010 3906)	D	(D)	D	D	D	(.00543 986)	D	D	- -	
19	D	D	(D)	(D)	D	(.0017 5884)	(D)	D	D	D	D	D	D	D	(.00114 001)	D	D	D	- -

a) D = Row strategy dominates column strategy by first-degree stochastic dominance; (D) = column strategy dominates row strategy by first-degree stochastic dominance

b) Figures are B-RAC values; those without parentheses are risk aversion coefficients below which row strategy dominates column strategy while those in parentheses are risk aversion coefficients below which column strategy dominates row strategy.

Table 6-4: Pairwise comparison matrix to investigate first-degree stochastic dominance and break-even risk aversion coefficients (B-RAC) for the dairy research projects ranked by cost-benefit ratio [a), b)]

RP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	- -																		
2	D	- -																	
3	D	D	- -																
4	D	D	(D)	- -															
5	D	(.02130 946)	(D)	(D)	- -														
6	D	D	(D)	(D)	D	- -													
7	D	D	(D)	D	D	D	- -												
8	D	D	(D)	(D)	D	(D)	(D)	- -											
9	D	D	(D)	(D)	D	(D)	(D)	D	- -										
10	D	D	(D)	(D)	D	D	(D)	D	D	- -									
11	D	D	D	D	D	D	D	D	D	D	- -								
12	D	D	D	D	D	D	D	D	D	D	(D)	- -							
13	D	D	(D)	(D)	D	D	(D)	D	D	.00225 4591	(D)	(D)	- -						
14	D	D	(D)	(D)	D	(D)	(D)	-.0613 4861	(D)	(D)	(D)	(D)	(D)	- -					
15	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(.00242 374)	- -				
16	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(.01878 088)	(D)	- -			
17	D	D	(D)	(D)	D	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	(D)	- -		
18	D	D	(D)	(D)	D	D	(D)	D	D	(D)	(D)	(D)	(D)	D	D	D	D	- -	
19	D	D	(D)	(D)	D	D	(D)	D	D	.00608 0613	(D)	(D)	(.00046 867)	D	D	D	D	D	- -

a) D = Row strategy dominates column strategy by first-degree stochastic dominance; (D) = column strategy dominates row strategy by first-degree stochastic dominance

b) Figures are B-RAC values; those without parentheses are risk aversion coefficients below which row strategy dominates column strategy while those in parentheses are risk aversion coefficients below which column strategy dominates row strategy.

The risk interval seems large enough to cover almost every possible attitude of the decision makers because values of 0.03 in risk averse and -0.03 in risk prone space represent extreme risk preferences compared to the scale of the projects' outcomes in terms of net present value and cost-benefit ratio. For the majority of the projects stochastic dominance can be stated in terms of FSD. However, a significant number of projects require GSD tests and the calculation of B-RACs to establish rank orders. By aggregating this information projects can be ranked in their sequence of their size of net present value and cost-benefit ratio within the boundaries of the risk interval.

Stochastic dominance results as presented in Tables 6-3 and 6-4 are difficult to comprehend and communicate in priority setting workshops, especially when the projects to be compared are numerous and dominance relationships are not always of the first and second order SD type. Risk ranking tables as developed in Table 6-5 and Table 6-6 offer a much better way of presentation by synthesising stochastic dominance results in graphical format without any loss of information. Risk ranking tables have several advantages over a tabular presentation of numbers because they:

- provide a complete rank ordering of decision alternatives at any risk aversion or risk proneness level expressed in terms of the risk aversion coefficient. Project ranking at a given risk aversion coefficient $r_a(x)$ can be derived simply by drawing a vertical line at the point of the risk aversion coefficient of interest and ordering projects in a sequence passing through the vertical line. Thus, the stability of rank ordering and the directions of rank changes along the whole preferences interval can be studied very well; and

- identify the exact stochastic dominance relationships between any pair of decision alternatives whether one of them are FSD, SSD, or have B-RAC values. For example, a decision alternative that does not share a rank with others is dominant over a set of decision alternatives and dominated by another set of decision alternatives by FSD rule. On the other hand, ranks that are shared between two or more decision alternatives indicate that all alternatives on this level have B-RAC while the choice of the best alternative depends on the preferences towards risk.

Risk ranking tables are presented in Table 6-5 based on net present value and in Table 6-6 based on the cost-benefit ratio. For a better interpretation, risk intervals are subdivided into three broad risk classes, namely, risk prone, risk averse and risk neutral with each class being defined by a lower and upper risk aversion coefficient. The subdivision into risk classes are based on classification from the literature but are corrected for the different outcome scale of the research projects' NPV compared to the farm income values in these studies, and for the use of different currencies (US $ versus KSh). The risk prone class was set to range from -0.03 to -0.0005; the almost risk neutral class from -0.0005 to +0.0005 and the risk averse class from +0.0005 to +0.03. It should be noted that both risk tables combine two different scales. For example, the risk interval close to risk neutrality is scaled down because of the special attention that should be given to it, while more distant risk ranges are presented in less detail by using a higher scale. However, subjectivity in defining those risk classes cannot be avoided since any classification that is taken from the literature is less reliable than an empirical elicitation of risk preference classes. Moreover, risk preferences in the literature (see Table 6-2) mostly concern farmers but not public research institutions.

Results from Table 6-5 reveal that project ranking based on NPV is very sensitive to decision makers' risk attitudes and this is true for the top level projects as well as for the lowest ranking projects. There are two projects, namely, RP 7 and RP 3 that share the first position with a B-RAC of 0.0008434. In the risk prone and risk neutral range the dominant project is RP 7 while many risk averse decision makers would prefer RP 3 because the risk of facing low NPV is considerably smaller for RP 3 than for RP 7. This can be examined too from the risk profiles of the two projects represented through PDF and CDF presented in Figure 6-2 and Figure 6-3. The CDFs of RP 3 and RP 7 have an intersection point below which RP 3 is superior – the probability of low NPV is smaller for RP 3 than for RP 7 – and above which RP 7 is superior due to higher probabilities of exceeding a given NPV.

Risk averse decision makers who prefer RP 3 are willing to forego the change of receiving high NPV offered by RP 7. The forgone change is indicated by the area between the two CDFs above the crossing point while the compensation in terms of reducing the risk of receiving low NPV is indicated by the area between the CDF below the crossing point. Comparing the size of both areas it can be concluded that decision makers who prefer RP 3 must have a strong aversion towards risk.

The second rank is shared between the three projects RP 4, RP 3, and RP 7 in order of increasing risk aversion. Whether or not to prefer RP 4 or RP 3 in the second place is a much more arbitrary decision than with RP 7 and RP 3 because of a break-even point very close to zero (also indicated by the location of the CDF crossing point around the median). This implies that a group of fairly risk neutral decision makers would not unanimously agree upon one single research projects. Those who are slightly risk averse would opt for RP 4 while slightly risk prone decision makers would prefer RP 4.

Table 6-5: Risk ranking table based on net present value (NPV)

Risk prone — **Risk neutral** — **Risk averse**

Zoom Zoom

- 0.03 | - 0.02 | - 0.01 | - 0.001 | -0.0005 | 0.00 | 0.0005 | 0.001 | 0.01 | 0.02 | 0.03

<table>
<tr><th>Rank</th><th colspan="13"></th></tr>
<tr><td>1</td><td colspan="7">RP 7 Appropriate forage / food intercropping systems</td><td colspan="6">RP 3 Diets for heifers and cows</td></tr>
<tr><td>2</td><td colspan="5">RP 4 On - farm testing of forage technologies</td><td colspan="2">RP 3 Diets for heifers and cows</td><td colspan="6">RP 7 Appropriate forage / food intercropping systems</td></tr>
<tr><td>3</td><td colspan="5">RP 3 Diets for heifers and cows</td><td colspan="8">RP 4 On - farm testing of forage technologies</td></tr>
<tr><td>4</td><td colspan="6">RP 15 Improved delivery system</td><td colspan="6">RP 6 Forage legumes</td><td colspan="1">RP 19 Policy study (Privat option)</td></tr>
<tr><td>5</td><td colspan="6">RP 6 Forage legumes</td><td colspan="2">RP 15 Improved delivery system</td><td colspan="5">RP 11 Cow fertility problems</td></tr>
<tr><td>6</td><td colspan="12">RP 19 Policy study (Privat option)</td><td colspan="1">RP 6 Forage legumes</td></tr>
<tr><td>7</td><td colspan="8">RP 11 Cow fertility problems</td><td colspan="5">RP 18 Policy study (Government option)</td></tr>
<tr><td>8</td><td colspan="3">RP 9 Legume seed production</td><td colspan="5">RP 18 Policy study (Government option)</td><td colspan="5">RP 15 Improved delivery system</td></tr>
<tr><td>9</td><td colspan="3">RP 18 Policy study (Government option)</td><td colspan="10">RP 9 Legume seed production</td></tr>
<tr><td>10</td><td colspan="13">RP 8 Feed conservation techniques</td></tr>
<tr><td>11</td><td colspan="2">RP 14 Indigenous disease control</td><td colspan="7">RP 16 Zero - grazing breeds</td><td colspan="4">RP 12 ECF - immunisation</td></tr>
<tr><td>12</td><td colspan="2">RP 16 Zero - grazing breeds</td><td colspan="2">RP 14 Indigenous disease control</td><td colspan="5">RP 12 ECF - immunisation</td><td colspan="4">RP 16 Zero - grazing breeds</td></tr>
<tr><td>13</td><td colspan="4">RP 12 ECF - immunisation</td><td colspan="7">RP 14 Indigenous disease control</td><td colspan="2">RP 10 Helminths disease</td></tr>
<tr><td>14</td><td colspan="1">RP 13 Mastitis control</td><td colspan="10">RP 10 Helminths disease</td><td colspan="2">RP 14 Indigenous disease control</td></tr>
<tr><td>15</td><td colspan="1">RP 10 Helminths disease</td><td colspan="12">RP 13 Mastitis control</td></tr>
<tr><td>16</td><td colspan="13">RP 17 Free - grazing breeds</td></tr>
<tr><td>17</td><td colspan="13">RP 2 Utilisation of locally available calf feeds</td></tr>
<tr><td>18</td><td colspan="10">RP 1 Utilisation of feeding commercial feeds</td><td colspan="3">RP 5 Frost prone forage varieties</td></tr>
<tr><td>19</td><td colspan="10">RP 5 Frost prone forage varieties</td><td colspan="3">RP 1 Utilisation of feeding commercial feeds</td></tr>
</table>

Figure 6-2: Risk profiles (cumulative distribution function) of the six highest ranking research projects based on net present value (KSh million)

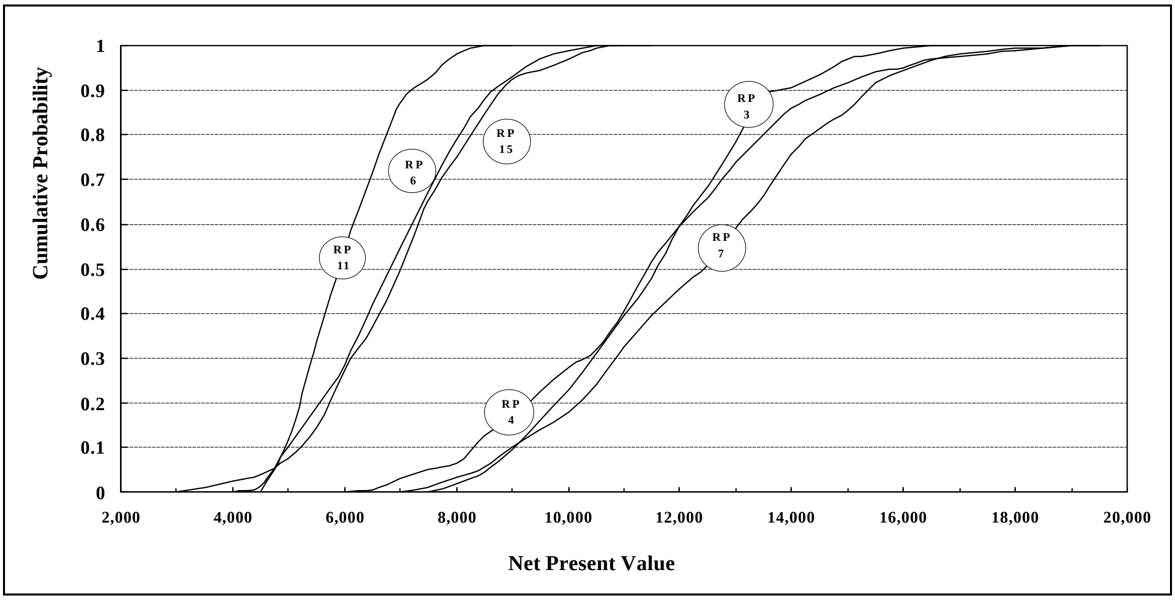


Figure 6-3: Risk profiles (probability density function) of the six highest ranking research projects based on net present value (KSh million)

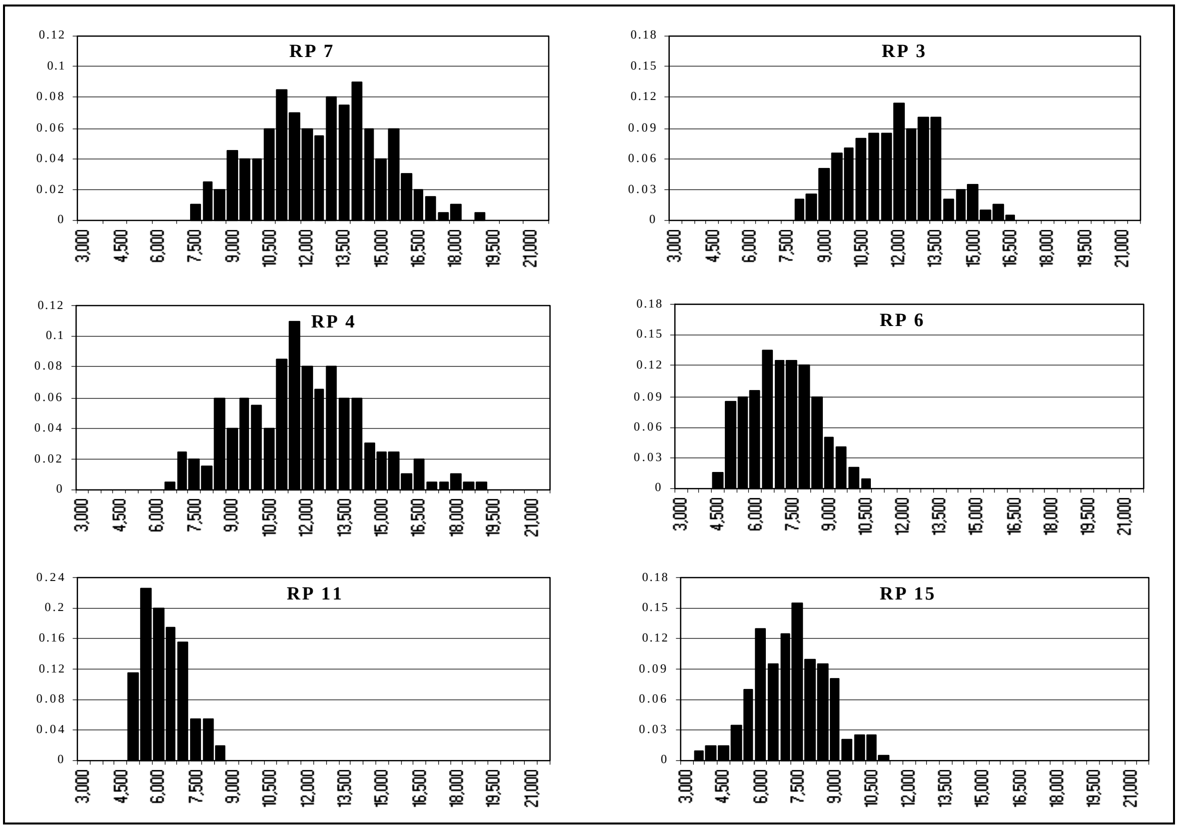


Table 6-6: Risk ranking table based on cost-benefit ratio (CBR)

Risk prone — **Risk neutral** — **Risk averse**

Zoom Zoom

Rank **- 0.03** **- 0.02** **- 0.01** **- 0.001** **-0.0005** **0.00** **0.0005** **0.001** **0.01** **0.02** **0.03**

<table>
<tr><td>1</td><td colspan="7">RP 11 Cow fertility problems</td></tr>
<tr><td>2</td><td colspan="7">RP 12 ECF - immunisation</td></tr>
<tr><td>3</td><td colspan="7">RP 3 Diets for heifers and cows</td></tr>
<tr><td>4</td><td colspan="7">RP 7 Appropriate forage / food intercropping systems</td></tr>
<tr><td>5</td><td colspan="7">RP 4 On - farm testing of forage technologies</td></tr>
<tr><td>6</td><td colspan="2">RP 13 Mastitis control</td><td colspan="2">RP 19 Policy study (Privat option)</td><td colspan="3">RP 10 Helminths disease</td></tr>
<tr><td>7</td><td colspan="2">RP 19 Policy study (Privat option)</td><td>RP 13 Mastitis control</td><td>RP 10 Helminths disease</td><td colspan="3">RP 19 Policy study (Privat option)</td></tr>
<tr><td>8</td><td colspan="3">RP 10 Helminths disease</td><td colspan="4">RP 13 Mastitis control</td></tr>
<tr><td>9</td><td colspan="7">RP 18 Policy study (Government option)</td></tr>
<tr><td>10</td><td colspan="7">RP 6 Forage legumes</td></tr>
<tr><td>11</td><td colspan="7">RP 9 Legume seed production</td></tr>
<tr><td>12</td><td>RP 14 Indigenous disease control</td><td colspan="6">RP 8 Feed conservation techniques</td></tr>
<tr><td>13</td><td>RP 8 Feed conservation techniques</td><td colspan="2">RP 14 Indigenous disease control</td><td colspan="4">RP 15 Improved delivery system</td></tr>
<tr><td>14</td><td colspan="3">RP 15 Improved delivery system</td><td colspan="2">RP 14 Indigenous disease control</td><td colspan="2">RP 16 Zero - grazing breeds</td></tr>
<tr><td>15</td><td colspan="5">RP 16 Zero - grazing breeds</td><td colspan="2">RP 14 Indigenous disease control</td></tr>
<tr><td>16</td><td colspan="7">RP 17 Free - grazing breeds</td></tr>
<tr><td>17</td><td colspan="6">RP 5 Frost prone forage varieties</td><td>RP 2 Util. of locally available calf feeds</td></tr>
<tr><td>18</td><td colspan="6">RP 2 Utilisation of locally available calf feeds</td><td>RP 5 Frost prone forage varieties</td></tr>
<tr><td>19</td><td colspan="7">RP 1 Utilisation of feeding commercial feeds</td></tr>
</table>

Figure 6-4: Risk profiles (cumulative distribution function) of the six highest ranking research projects based on cost-benefit ratio (CBR)

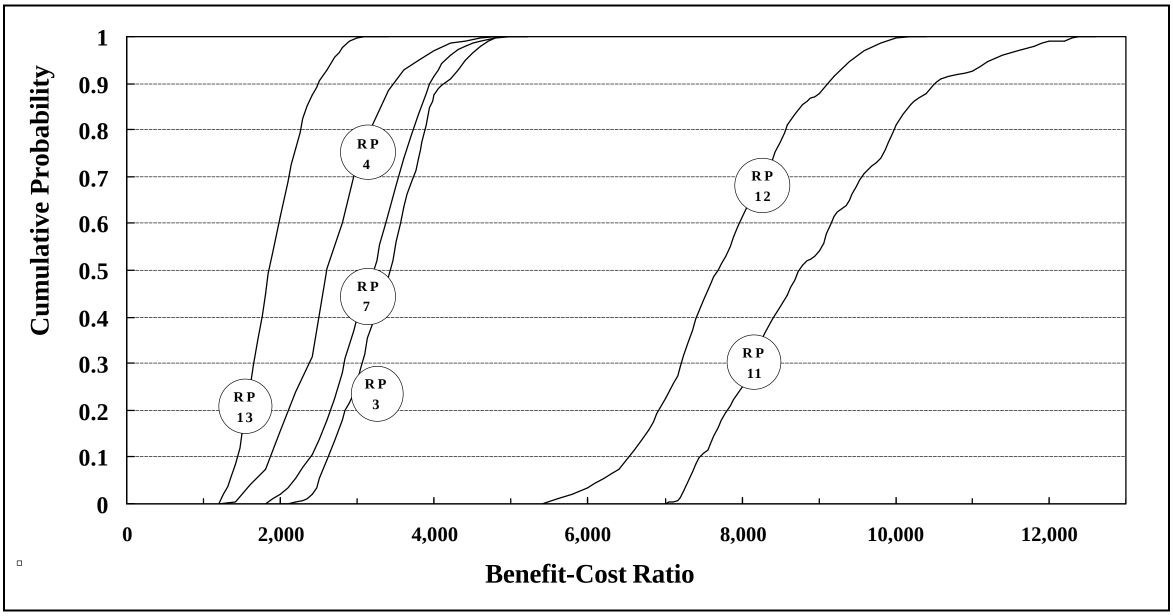
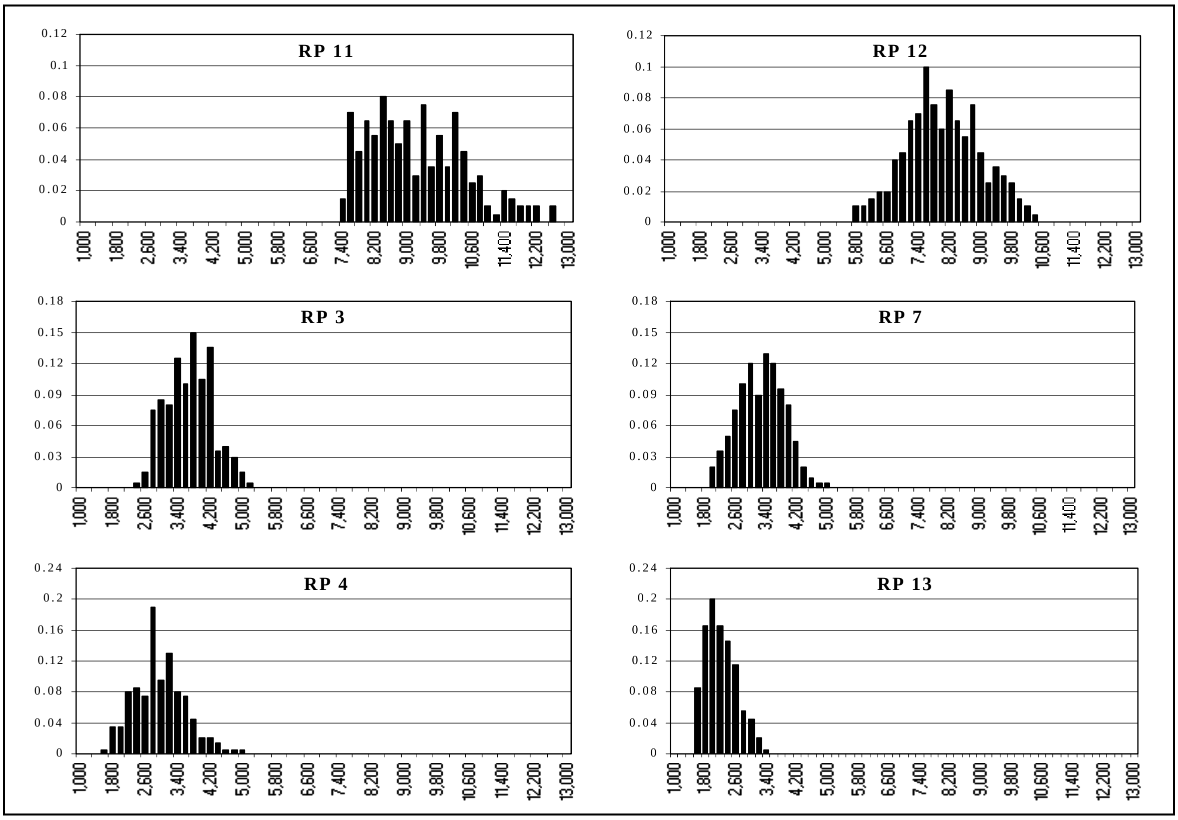


Figure 6-5: Risk profiles (probability density function) of the six highest ranking research projects based on cost-benefit ratio (CBR)



Other research projects whose B-RAC are close to zero are RP 14 and RP 12 when moving further down the list. For the remaining projects dominance relations are rather clear-cut since all critical B-RACs are located in the more extreme risk space whose practical relevance for the decision makers' actual risk attitude may be quite limited. Projects whose ranks are most sensitive to changing risk attitudes are RP 15 and RP 14. RP 15 would fall from the 4th rank to the 8th rank and RP 14 from the 11th to the 14th rank when risk aversion is increased. So, it can be concluded for these particular projects that, in view of the significant variability in ranks, the formal treatment of risk matters really when project choices are to be made on the basis of these ranking tables. For the other projects, rank differences are less dramatic, rarely exceeding one or a maximum of two positions.

Project ranking by CBR criterion is much less affected by risk attitudes as Table 6-6 shows. The top 5 ranking projects are all dominant by FSD rule indicating that risk has no influence on the ranking at all. This can be studied from the risk profiles showing that the CDF of the top 5 projects do not cross (see Figure 6-4). The CDF of RP 11 as the best performing in terms of CBR lies totally to the right of all other CDFs. Differences in research costs cause a reduction in risk sensitivity in project ranking when research impact is expressed in CBR, which is the recommended criterion for comparing projects if resources are limited. Moving down the list the picture becomes slightly different. There are two places – one between position 6 and 8 and the other between position 12 and 15 – where risk matters and project ranking is affected by different risk preference assumptions.

To summarise some of the major findings, one can conclude that for the dairy priority setting exercise the formal incorporation of risk into the evaluation of the projects' return does not lead to different outcome measures (because of the additivity of the stochastic variables) in comparison to a deterministic treatment of the net yield increase parameter. However, the ranking of projects is not as clear-cut as would be suggested from a deterministic analysis. Project ranks are, by and large, risk sensitive which is surprising in view of the relatively small set of only 19 projects. This is especially indicated for the NPV criterion and to a somewhat lower degree for the CBR criterion.

At many locations projects ranks are sensitive to risk not only in the presence of rather extreme assumptions regarding risk attitudes but also very close to risk neutrality. This sensitivity has two sources: one is that there are several groups of projects with similar NPV, and the other is that induced positive correlation increases the variability of the NPV around its mean (in terms of standard deviation) leading to intersections of the CDF. It can be suggested that without correlation ranks would be more stable over the screened risk interval due to lower variability in the CDF.

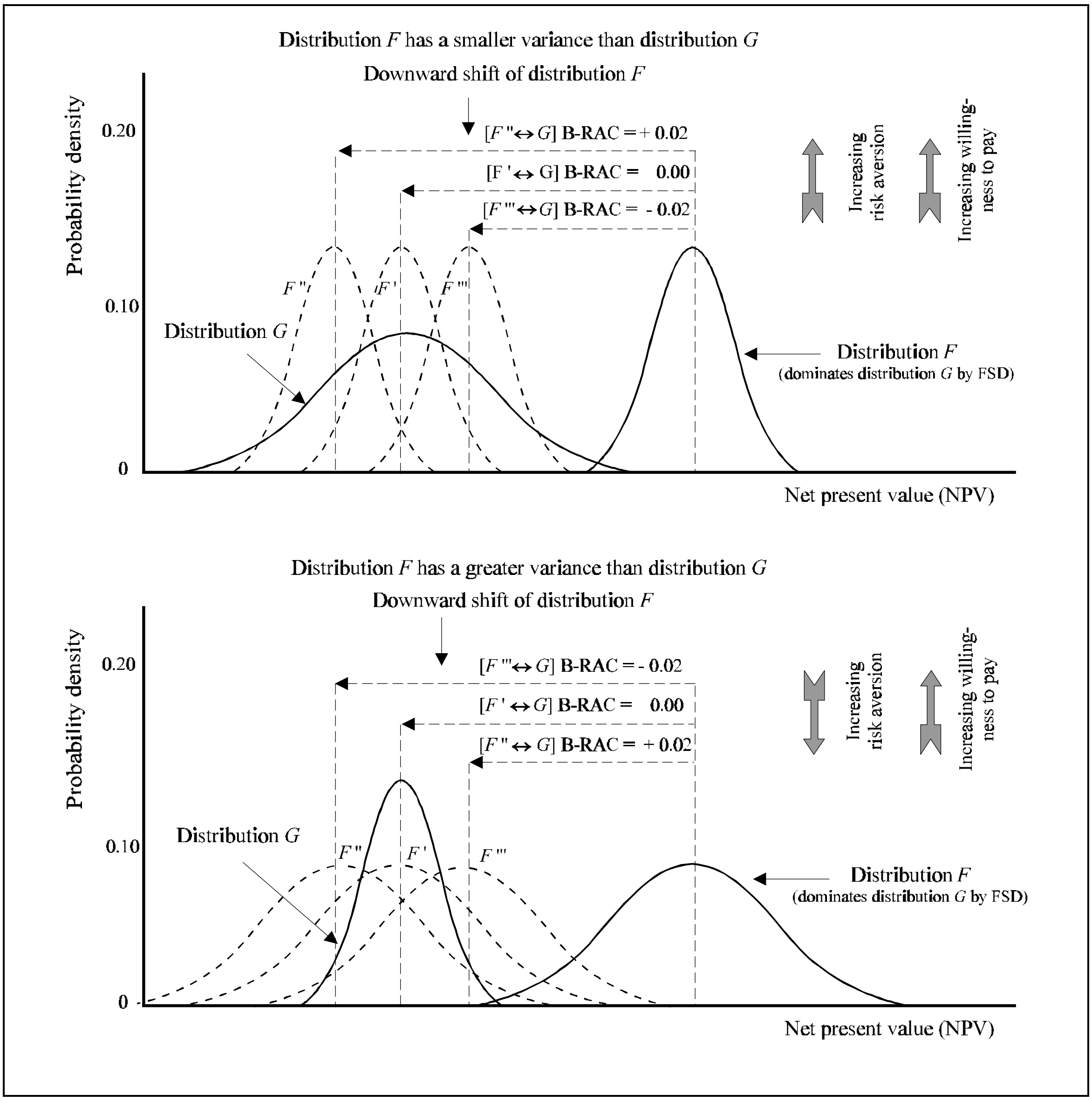
6.3 The Value of Stochastic Dominance

Once stochastic dominance relations between each pair of projects are established one may proceed with another type of analysis that is aimed at an economic valuation and quantification of stochastic dominance. When project outcomes are expressed as single point estimates such as expected NPV the value of the dominance between two projects is just the difference between their expected NPV. Some complication is added when outcomes are stochastic and the value of dominance must be assessed. The "riskroot" program offers the possibility of making a quantitative assessment of the stochastic dominance based on the "willingness to pay" concept. More precisely, it measures the amount that a decision maker defined by his/her risk aversion coefficient would be willing to pay for the right to use the dominant distribution instead of the inferior distribution. In practise the "willingness to pay" translates into identifying the magnitude of a downward parallel shift of the dominant distribution that would be necessary to eliminate the dominance and produce a change in the efficient set.

The willingness to pay concept is reproduced in Figure 6-6 by an example in which a distribution *F* represents a project's NPV probability density distribution that dominates another distribution *G* by FSD. Let us assume that a decision maker's risk preference is known and can be represented by $r_a(x)$, = +0.02 (strongly risk averse). Then, the willingness to pay for the use of the dominant distribution *F* is exactly the amount by which the distribution *F* is shifted downward (indicated by *F* " in the upper part of Figure 6-6) to *F* " until the dominated distribution *G* and the distribution *F* " have a B-RAC at $r_a(x)$ = +0.02. The willingness to pay is somewhat smaller for a risk neutral (represented by the downward shift of distribution *F* to *F* ') and risk prone (downward shift of distribution *F* to *F* "') decision makers.

The willingness to pay concept can be easily extended to a class of decision makers defined by their risk preference interval, for example between -0.02 ≤ $r_a(x)$ = ≤+0.02 as indicated in Figure 6-6. By defining the risk interval in terms of lower and upper bound risk aversion coefficients the magnitude of the parallel shift is then set between an interval representing the maximum and minimum willingness to pay. The upper bound measures the shift in the dominant distribution that results in the inferior distribution being preferred to the dominant distribution. This reflects the maximum willingness to pay for any decision maker for the right to use the dominant distribution, but some decision makers would be willing to pay a smaller amount. According to Figure 6-6, the maximum willingness to pay would be the amount equivalent to the downward shift of distribution *F* to *F* " (upper part of Figure 6-6). Any decision maker whose risk preference is below +0.02 (less risk averse) would be willing to pay less. The lower bound measures the shift in the dominant distribution that produces an efficient set with both distributions as members. This measures the amount that at least one decision maker in the preference group is willing to pay to use the dominant distribution and reflects the minimum willingness to pay since other decision makers are willing to pay more (GOH, et al., 1989, p. 180). This would be indicated by the shift of distribution *F* down to *F* ''' (upper part of Figure 6-6).

Figure 6-6: The value of stochastic dominance measured by a downward shift in the dominant distribution



In general, the dominant distribution (distribution *F*) should be dominant by FSD, then upper and lower risk preferences can be set freely. But it can also accommodate distributions that are non FSD, respectively discriminate against other distributions only by

GSD. In that case, the B-RAC between the two distributions to be compared constitutes the upper limit of the risk preference interval.

Whether the upper risk bound defines the minimum or the maximum willingness to pay depends on the direction of the willingness to pay along the risk interval which, in turn, depends on the variance of the two distributions. If the dominant distribution exhibits a smaller variance than the inferior distribution (upper part of Figure 6-6), the willingness to pay increases towards risk aversion. The lower bound then constitutes the minimum and the upper bound the maximum willingness to pay. If the dominant distribution has a higher variance, then the willingness to pay increases in an opposite direction to risk aversion.

Initially used for the valuation of information strategies, the willingness to pay concept is applicable to several other fields of interest and can be applied, e.g., to the valuation of agricultural inputs, provision of information, investment decisions and even agricultural policies that all have an effect on the return distributions. In this study, the primary aim is to provide decision makers with a comparative measure that is able to quantify the difference in project performance given any assumption regarding group risk preferences.

Table 6-7 and Table 6-8 present selected results of the value of stochastic dominance for the six top ranking projects in terms of NPV and CBR with RP 7 and RP 11 taken as the reference projects. The risk interval was specified to range between $r_a(x)$ = +0.02 and -0.02. Table 6-7 shows, for example, that the willingness to pay for the right to use RP 7 instead of RP 15 amounts, at its maximum value, to around 7,847 million KSh for risk prone decision makers and around 3,984 million KSh as the minimum value for risk averse decision makers. Risk neutral decision makers would be willing to pay just the difference between the expected NPV. The size of the willingness to pay becomes larger when moving into risk prone direction indicating that the dominant research project RP 7 must have a higher variance than all other projects in this group.

An alternative interpretation of the willingness to pay from the point of view of the inferior distribution may be used to examine how research parameters need to be adjusted in order to exactly compensate for the willingness to pay. Instead of a downward shift in the dominant distribution, now the focus is on the inferior distribution, and the size of a parallel upward shift of the inferior distribution is taken as the value of the willingness to accept compensation for renouncing the use of the dominant distribution. This way, one can examine how far e.g., net yield increase or adoption rates of an inferior project need to be improved in order to cause an upward shift in the outcome distribution that is equivalent to the willingness to accept compensation. By so doing, Table 6-7 and 6-8 show these results for the net yield increase and adoption rates parameters of inferior projects. Net yield increase values indicate the magnitude of a parallel shift in the triangular distribution which means that each point of the distribution – the lowest, most likely and highest expected yield increase for any region – is augmented by the same amount. Adjustments regarding higher adoption rates are made only with respect to the maximum adoption level.

Table 6-7: The value of stochastic dominance for selected top ranking projects based on net present value

	Lower and upper bounds of the willingness to pay for the use of RP 7 (NPV in KSh million)			Equivalent change in selected input parameter: net yield increase and adoption maximum					
	Risk aversion coefficient $r_a(x)$			Net yield increase (YI)			Increase of adoption maximum (AM)		
Project type	-0.02 Risk prone	0.00 Risk neutral	0.02 Risk averse	-0.02	0.02	0.00	-0.02	0.02	0.00
RP 3	2,530.63	767.85	-----	2.8	1.1	---	12	3	---
RP 4	791.76	766.29	738.12	1.2	1.1	1.0	4	3.5	3
RP 15	7,846.98	5,292.77	3,983.99	24	18	12	38	25	18
RP 6	8,226.74	5,456.20	2.944.38	18	11	6	33	22	14
RP 11	10,351.47	6,299.56	2,430.44	10	5.5	2	20	/	/

For example, sensitivity analysis for RP 11 has found that an improvement in yield increase over all AEZ of 10 per cent points would cause an increase in NPV of around 10,352 million KSh for any state of nature. The same NPV increase could have been achieved with an increase in the adoption maximum of 20 per cent points from 51.32 per cent to 71.32 per cent. Table 6-7 also shows that for some cases (e.g., RP 11) increasing the maximum adoption level is not sufficient to lift NPV up to the desired level because of the initial high adoption maximum close to 100 per cent. Table 6-8 shows the results for the same type of analysis carried out for the cost-benefit ratio but with a different project set based on the CBR performance. In contrast to the NPV example, the calculated shifts in the CBR distributions cannot serve as an indicator for the willingness to pay. Instead, the willingness to pay was approximated by the parallel shift in the gross research benefit distribution as an equivalent to the shift in the CBR assuming research costs remain unchanged. In the same way, reduction in research costs were calculated given constant gross research benefits.

Table 6-8: The value of stochastic dominance for selected top ranking projects based on cost-benefit ratio

	Lower and upper bounds of the CBR differences (reference is RP 11)			Equivalent change in gross research benefits or decrease in research costs (KSh million)					
	Risk aversion coefficient			Gross research benefits			Research costs		
Project type	-0.02 Risk prone	0.00 Risk neutral	0.02 Risk averse	-0.02	0.02	0.00	-0.02	0.02	0.00
RP 12	2,083.49	1,707.52	1,566.27	650	533	489	0.0640	0.0546	0.0508
RP 3	7,400.89	5,552.06	4,828.54	24,045	18.039	15,688	2.1650	1.9490	1.8387
RP 7	7,604.47	5,959.54	5,369.76	29,536	23,148	20,857	2.7097	2.5010	2.4069
RP 4	7,826.59	6,293.62	5,657.63	31,798	25,571	22,987	2.9475	2.7628	2.6669
RP 13	9,099.68	7,038.01	5,858.88	4,000	3,094	2,576	0.3535	0.3343	0.3189

In this example, the willingness to pay generally increases from risk aversion to risk proneness. As was outlined earlier, project ranks according to CBR are much less affected by changing risk attitudes, thus, ranks are much more stable. This implies that the amount by which gross benefits need to be increased and research costs need to be reduced in order to compete with the top project RP 11 is immense. This holds true for every subordinate project.

6.4 Inferential Statistics for Stochastic Dominance Analysis

The ability to rank risky alternatives makes stochastic dominance a very versatile and powerful decision tool. However, like any other statistical analysis, the application of stochastic dominance tests are also subject to sampling errors. Empirical studies that have applied stochastic dominance criteria to comparing decision alternatives often overlooked or simply ignored the implication of sampling errors for the reliability of stochastic dominance results. This section describes the bootstrapping technique, which belongs to the group of re-sampling techniques, to be used as a means to test for the uncertainty associated with stochastic dominance test results. An application of bootstrapping is presented for a selected set of dairy research projects from the case study. However, it should be noticed that the use of bootstrap in the context of stochastic dominance analysis should be rather the exception than the rule because of considerable effort and time requirement. Instead, bootstrap should be used selectively, especially when decision alternatives have similar outcome distributions and when sampling errors are suspected to be high; so, for example, in the absence of efficient sampling techniques or truncation of CDFs in stochastic dominance programs.

KROLL and LEVY (1980) use the following definition of sampling errors: we may have that *F* dominates *G* in the population but the two empirical distributions intersect, hence distributions *F* and *G* will be in the ex-post FSD efficient set. Another possible error is that *F* and *G* corresponding to the population intersect but *F* and *G* in the sample do not intersect (see Table 6-9).

- Error type I: For two prospects, one dominates the other in the population but no dominance is found in the sample.
- Error type II: Neither prospect dominates in the population but dominance is found in the example; or one prospect dominates the other in the population while an opposite dominance relationship is found in the sample.

Table 6-9: Stochastic dominance outcome and error classification

		Dominance relation in the population		
		F dominates *G*	*G* dominates *F*	No dominance
Sample findings	*F* dominates *G*	No error	Type II	Type II
	G dominates *F*	Type II	No error	Type II
	No dominance	Type I	Type I	No error

Source: KROLL and LEVY (1980), as cited in NELSON and POPE (1991, p. 1184)

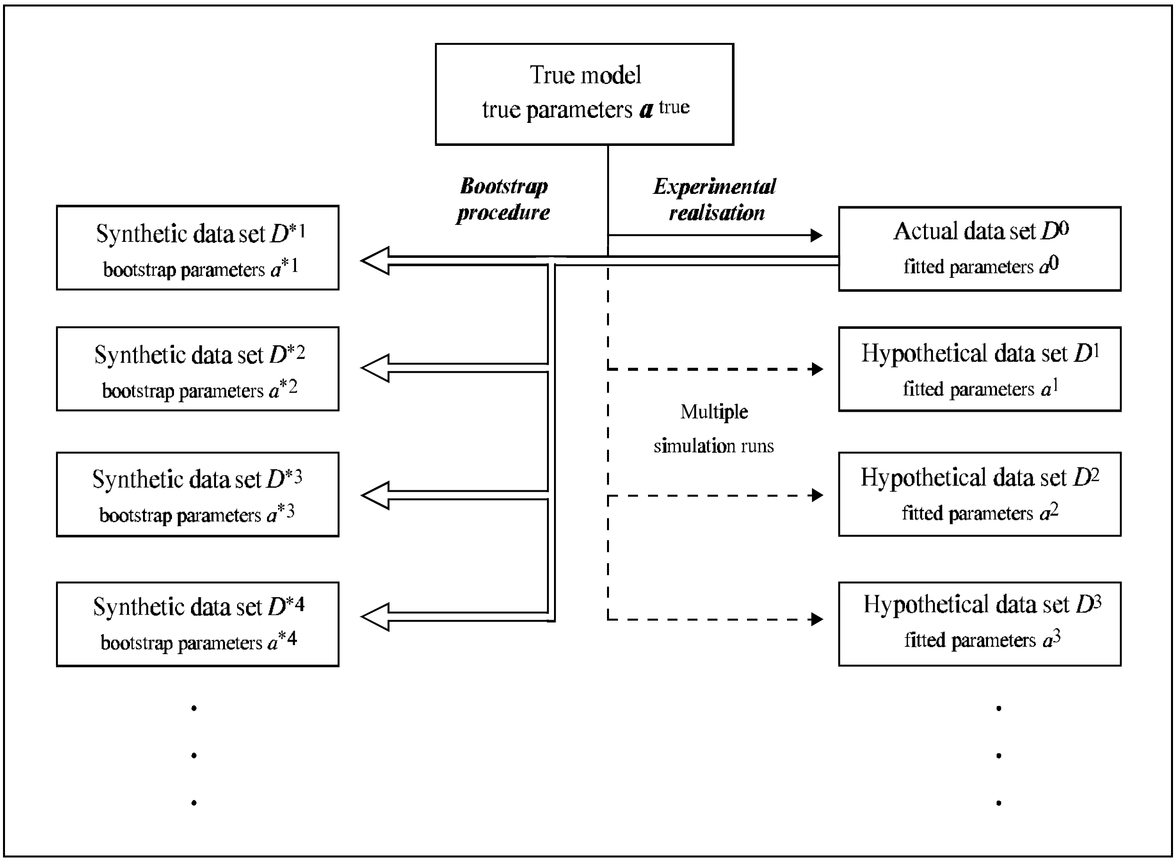
The analysis of the sample versus population stochastic dominance can be done by simulation and by exact statistical tests. LEVY and KROLL (1980), KROLL and LEVY (1980), POPE and ZIEMER (1994), and others have used simulation techniques to gain insights into the error distributions by drawing random samples from known distributions and by comparing the resulting SD results between the empirical and the known distributions. The main result of these simulations is that the power of SD tests is relatively low due to high incidence of ascertaining wrong dominance relationships. Standard tests have been applied with some success to test for stochastic dominance, especially for FSD. Under the Null-hypothesis that the CDF of prospect *F* equals the CDF of prospect *D*, the well known Kolmogorov-Smirnov (one-sided K-S test) and Wilcoxon-Mann-Whitney procedures can be applied to test whether a pair of distributions emanate from the same population. Also, SCHMID and TREDE (1994) developed a test procedure suitable for FSD. All these tests are specific to FSD and fail to recognise any other dominance relationship, i.e., to examine SSD results or break-even risk aversion coefficients in GSD.

NELSON and POPE (1991) propose the use of bootstrap techniques as described in EFRON (1979), and EFRON and GONG (1983) to overcome much of the analytical intractability of establishing exact statistical tests. Bootstrapping is a non-parametric or distribution free technique that can derive various estimators and confidence limits as an indicator for the surrounding uncertainty of fitted estimators and also can increase the power of SD tests by improving the usually inadequate empirical distribution function (EDF) as an estimator of the cumulative density functions (CDF). The essentials of bootstrap are outlined in Figure 6-9 which shows the conceptual scheme of bootstrapping in contrast to other simulation experiments for measuring a set of statistical parameters.

Assume that there is some underlying true set of unknown parameters a^{true} and a statistical realisation as a measured or simulated data set D^0 along with random measurement errors (see Figure 6-7). From the known data set D^0 values for the parameters a^0 can be derived that represent a^{true}. Because replicated experiments or realisation of the true model would result in slightly different data sets D^1, D^2,..., etc., and fitted parameters, denoted here by a^1, a^2,..., etc., we may have a set of different parameters a^i that occur with some probability distribution. If one could determine the distribution of the a^i - a^{true}, then the quantitative uncertainty of the parameter a^0 from the actual data set could be estimated.

Without knowing a^{true} one can first use a simulation strategy to generate a sufficient number of hypothetical data sets by multiple simulation runs from the assumed PDF to receive a^i - a^0, or alternatively, generate synthetic data sets D^{*i} from the actual data set with the same number of measured points by bootstrap procedures to receive a^{*i} - a^0, where a^{*i} is the fitted parameter of the synthetic data set D^{*i}. The main proposition of the bootstrap is that the way in which random errors enter the experimental realisation from the true model generating the actual data set is the same for the bootstrap samples from this data set. Therefore, the probability distribution of the bootstrapped parameters around a^0 (a^{*i} - a^0) is a good approximation to the probability distribution of the fitted parameter around a^{true} (a^i - a^{true}). Bootstrapping has several advantages over other strategies because it does not require the actual data set to be fitted to a theoretical or empirical distribution and, perhaps more importantly, multiple runs from the simulation model can be substituted by simply re-sampling from the final outcome distributions. The bootstrap procedure can be easily applied to order statistics of the empirical distribution functions (EDF) and CDF that stochastic dominance tests depend heavily on, and can calculate the bias and standard deviation of the order statistics by re-sampling only from the information found in the original random sample. The standard deviations reveal to decision makers the degree of uncertainty which surrounds the parameter estimates being used to establish dominance relationships.

Figure 6-7: Bootstrap sampling strategy



Source: Modified, after PRESS et al. (1992, p. 685-686)

According to NELSON and POPE (1991, p. 1182) bootstrapping complements the EDF in very significant ways, first: in the comparison of two specific examples, bootstrapped estimates of bias and standard deviations can help decision makers to locate the order statistics about which they are most uncertain, and second: the ability of bootstrapping to smooth order statistics and to avoid inadvertent intersection of the cumulative distribution significantly increases the power of the crossing algorithm when dominance does exist in the population.

6.4.1 Bootstrap Sampling Strategy

The aim of the bootstrap procedure in this example is to determine confidence intervals for the stochastic dominance test results already outlined in this chapter including FSD and GSD, and to analyse whether tests results are susceptible to changes, e.g., from FSD to GSD and vice versa. The application of the bootstrap used here requires only a simple adaptation of the general bootstrap procedure and is described in NELSON and POPE (1991). For simplicity, let assume a pair of research projects, project *A* and project *B*, whose outcomes are represented through a distribution of n = 200 initial net present values $x^A_{(1)}$, $x^A_{(2)}$,..., $x^A_{(n)}$ for project *A*, and $x^B_{(1)}$, $x^B_{(2)}$,..., $x^B_{(n)}$ for project *B*. Ordering the respective net present values results in the two vectors of ordered net present values denoted as X^A for project *A* and X^B for project *B* (Figure 6-8). The next step is to re-sample n = 200 observations from each of the net present value distributions of X^A and X^B to receive the first bootstrapped sample $x^{A*1}_{(1)}$, $x^{A*1}_{(2)}$, ..., $x^{A*1}_{(n)}$ for project *A*, and $x^{B*1}_{(1)}$, $x^{B*1}_{(2)}$, ..., $x^{B*1}_{(n)}$ for project *B*.

Ordering the first bootstrap sample values gives the order statistics needed to calculate the differences $d^{*1}_{(1)}$,. $d^{*1}_{(2)}$, ..., $d^{*1}_{(n)}$ representing the difference in net present value between project *A* and project *B* at each order. The present application of bootstrapping then repeats this process *K*-times with the generation of *k* independent bootstrap replications.[8] Averaging the *k* ordered bootstrap differences then gives the mean of the difference as:

$$\overline{d}^{*}_{(i)} = \frac{1}{K}\sum_{k=1}^{K} d^{*k}_{(i)} \qquad (3)$$

At any order *i*, the estimated bias of the difference $d_{(i)}$ from the initial sample value $x^A_{(i)}$ and $x^B_{(i)}$ is then $d^*_{(i)}$ - $d_{(i)}$, and the estimated standard deviation is $\sigma_{d(i)}$. The standard deviation $\sigma_{d(i)}$. provides a measure of the uncertainty associated with each difference $d_{(i)}$, and is defined as:

$$\sigma d_{(i)} = \left[\frac{1}{K-1}\sum_{k=1}^{K}(d^{*k}_{(i)} - \overline{d}^{*}_{(i)})^2\right]^{1/2} \qquad (4)$$

By combining $\sigma_{d(i)}$ and the $d_{(i)}$ as $d_{(i)} \pm 2\sigma_{d(i)}$ one can construct a two-standard deviation interval which resembles a confidence interval for the $d_{(i)}$ given a confidence level of 95 per cent. NELSON and POPE (1991, p. 1185) replaced the $d_{(i)}$ by the bootstrapped mean $\overline{d}^{*}_{(i)}$ values to receive the two-standard deviation confidence intervals $\overline{d}^{*}_{(i)} \pm 2\sigma_{d(i)}$ with smoothed interval boundaries. In a next step, the confidence intervals over all orders *i* can be

[8] According to PRESS et al. (1992, p. 687) the minimum re-sample size is generally around 100. Sizes greater than 500 do not appreciably improve the accuracy of bootstrap in many applications.

aggregated to confidence bounds that can serve to detect the location of the highest uncertainty and critical difference levels that might seriously affect FSD tests (see Figure 6-9). In the last step, a GSD analysis is then employed to a group of selected projects based on the mean of the difference and the lower and upper bound of the confidence intervals for the bootstrap differences $d_{(i)}$ to obtain the mean, lower and upper bound of the B-RACs defining the 95 per cent confidence interval for the initial B-RAC values.

Figure 6-8: Bootstrapping procedure for the net present value differences of two research projects *A* and *B*

$$X^A = \begin{bmatrix} x^A_{(1)} \\ x^A_{(2)} \\ \vdots \\ \vdots \\ x^A_{(n)} \end{bmatrix} \qquad X^{A^*} = \begin{bmatrix} x^{A*1}_{(1)} & x^{A*2}_{(1)} & \cdots & x^{A*K}_{(1)} \\ x^{A*1}_{(2)} & x^{A*2}_{(2)} & \cdots & x^{A*K}_{(2)} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ x^{A*1}_{(n)} & x^{A*2}_{(n)} & \cdots & x^{A*K}_{(n)} \end{bmatrix}$$

$$X^B = \begin{bmatrix} x^B_{(1)} \\ x^B_{(2)} \\ \vdots \\ \vdots \\ x^B_{(n)} \end{bmatrix} \qquad X^{B^*} = \begin{bmatrix} x^{B*1}_{(1)} & x^{B*2}_{(1)} & \cdots & x^{B*K}_{(1)} \\ x^{B*1}_{(2)} & x^{B*2}_{(2)} & \cdots & x^{B*K}_{(2)} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ x^{B*1}_{(n)} & x^{B*2}_{(n)} & \cdots & x^{B*K}_{(n)} \end{bmatrix}$$

$$\mathrm{D} = X^A - X^B = \begin{bmatrix} d_{(1)} \\ d_{(2)} \\ \vdots \\ \vdots \\ d_{(n)} \end{bmatrix} \qquad \mathrm{D}^* = X^{A^*} - X^{B^*} = \begin{bmatrix} d^{*1}_{(1)} & d^{*2}_{(1)} & \cdots & d^{*K}_{(1)} \\ d^{*1}_{(2)} & d^{*2}_{(2)} & \cdots & d^{*K}_{(2)} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ d^{*1}_{(n)} & d^{*2}_{(n)} & \cdots & d^{*K}_{(n)} \end{bmatrix}$$

X^A is a $n\times1$ vector of the ordered n net present value estimates for project A

X^{A^*} is a $n\times K$ matrix of the k ordered bootstrap samples for project A

X^B is a $n\times1$ vector of the ordered n net present value estimates for project B

X^{B^*} is a $n\times K$ matrix of the k ordered bootstrap samples for project B

D is a $n\times1$ vector of the differences of the net present value estimates for project A and B

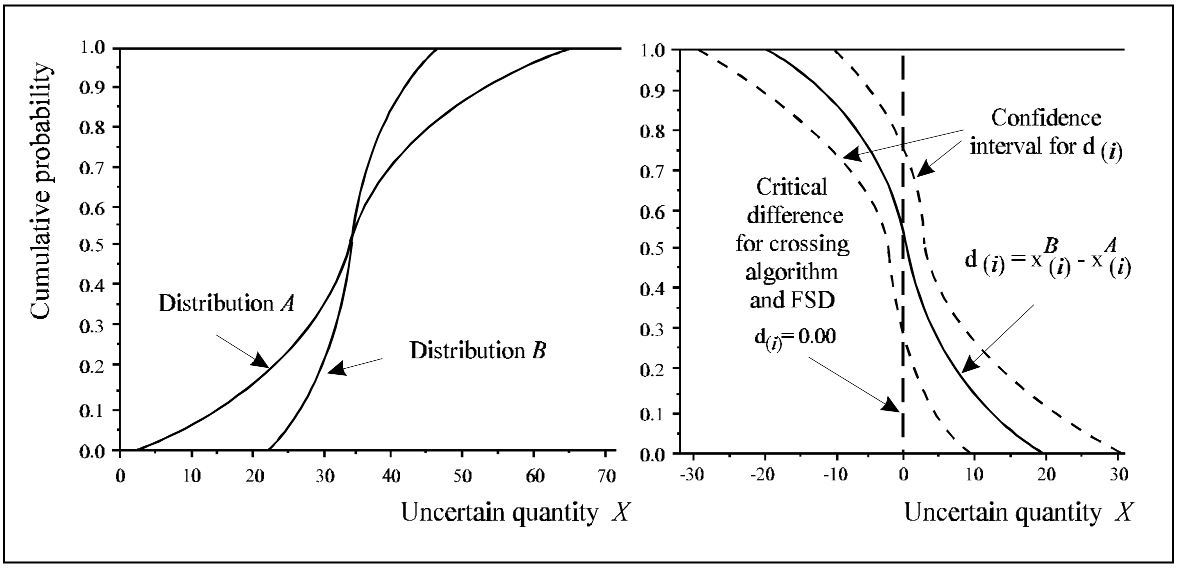
D^* is a $n\times K$ matrix of the differences of the net present value estimates for the K bootstrap samples

In the following example the bootstrapping procedure was applied to a group of 5 top ranking dairy projects to examine the robustness of the empirical stochastic dominance results. In accordance to NELSON and POPE (1991, p. 1185) confidence intervals are constructed by calculating the two-standard deviation intervals around the bootstrapped mean $\bar{d}^*_{(i)}$ and not around the $d_{(i)}$ as it can be seen from the smooth boundaries in Figure 6-10.

Many of the projects dominate other projects only by GSD which poses an interesting question as to whether GSD can be confirmed or may be reduced to a FSD relationship. On the other hand, given a FSD relationship detected from the prior SD analysis, it may be interesting to know whether FSD remains or may change to GSD. Now, three interesting examples are depicted where these questions can be studied especially well. These are the project pairs (RP 3, RP 7), (RP 6, RP 16), and (RP 4, RP 7), (see Figure 6-10).

The first two pairs have in common highly risk averse B-RAC values, thus, the chance that GSD may change to FSD within the confidence limit is quite high. On the other hand, RP 7 dominates RP 4 by FSD within the third pair, but here FSD is rather weak due to the closeness of the CDFs and may easily change to GSD.

Figure 6-9: Defining confidence bounds for the differences between the empirical cumulative distribution functions (CDF) of a project pair *A* and *B*



Source: Modified, after NELSON and POPE (1991, p. 1186-1187)

6.4.2 Bootstrap Results

The process of bootstrapping has an important effect on the differences between the CDFs such as the one depicted in Figure 6-10. The averaging process used to estimate the bias generates smoothed values $\overline{d}^*_{(i)}$ as by-products while the empirical CDFs exhibit much greater noise. However, the bias between bootstrapped $d^*_{(i)}$ and empirical differences $d_{(i)}$ is not significant at all even at the left-hand tail of the CDFs.

This implies that using bootstrap $\overline{d}^*_{(i)}$ values instead of the empirical $d_{(i)}$ would lead to the same conclusion with respect to FSD and would result in slightly different values of the B-RAC between the project pairs RP 3 with RP 7 and RP 6 with RP 19.[9] Intuitively, this may stem from the fact that sampling errors are kept to a minimum due to the use of the Latin-Hypercube sampling technique instead of Monte Carlo sampling. Furthermore, samples were drawn from a closed-form distribution (triangular distribution) and not from an open-form distribution (e.g., the normal distribution), thus, keeping the incidence of positive and negative outliers from the tails of the distributions at a low level.

Figure 6-10 shows the confidence bands derived from the confidence intervals at each order of the differences $d_{(i)}$ from the sample. Is does not come at a surprise that the confidence bands tend to reveal greater uncertainty in the tails of the CDFs compared to their middle range except the left-hand tails where uncertainty is generally smaller. From the present mean, lower and upper bootstrap $d^*_{(i)}$ confidence intervals for the stochastic dominance relationship were derived making several runs for each $d^*_{(i)}$ type with the "riskroot" program to calculate FSD and the break-even risk aversion coefficients. These results are outlined in Table 6-10 for a set of 10 pairs of research projects.

The examination of the first project pair (RP 3, RP 7) in Figure 6-10 shows that the existence of a B-RAC coefficient between both projects – which implies that they cannot be discriminated by first-degree stochastic dominance – is rather stable and can be confirmed by a confidence level of over 95 percent (see Table 6-10). Similarly, a initial break-even risk aversion coefficient has been reported for the second project pair (RP 6, RP 19). But here, the situation is less clear-cut since it cannot be excluded that B-RAC may change to ordinary FSD. So, the confidence level at which FSD could be rejected is somewhat less than 95 per cent. Another interesting example is the third project pair (RP 4. RP 7) in Figure 6-10 where initially RP 7 dominates RP 4 by FSD.

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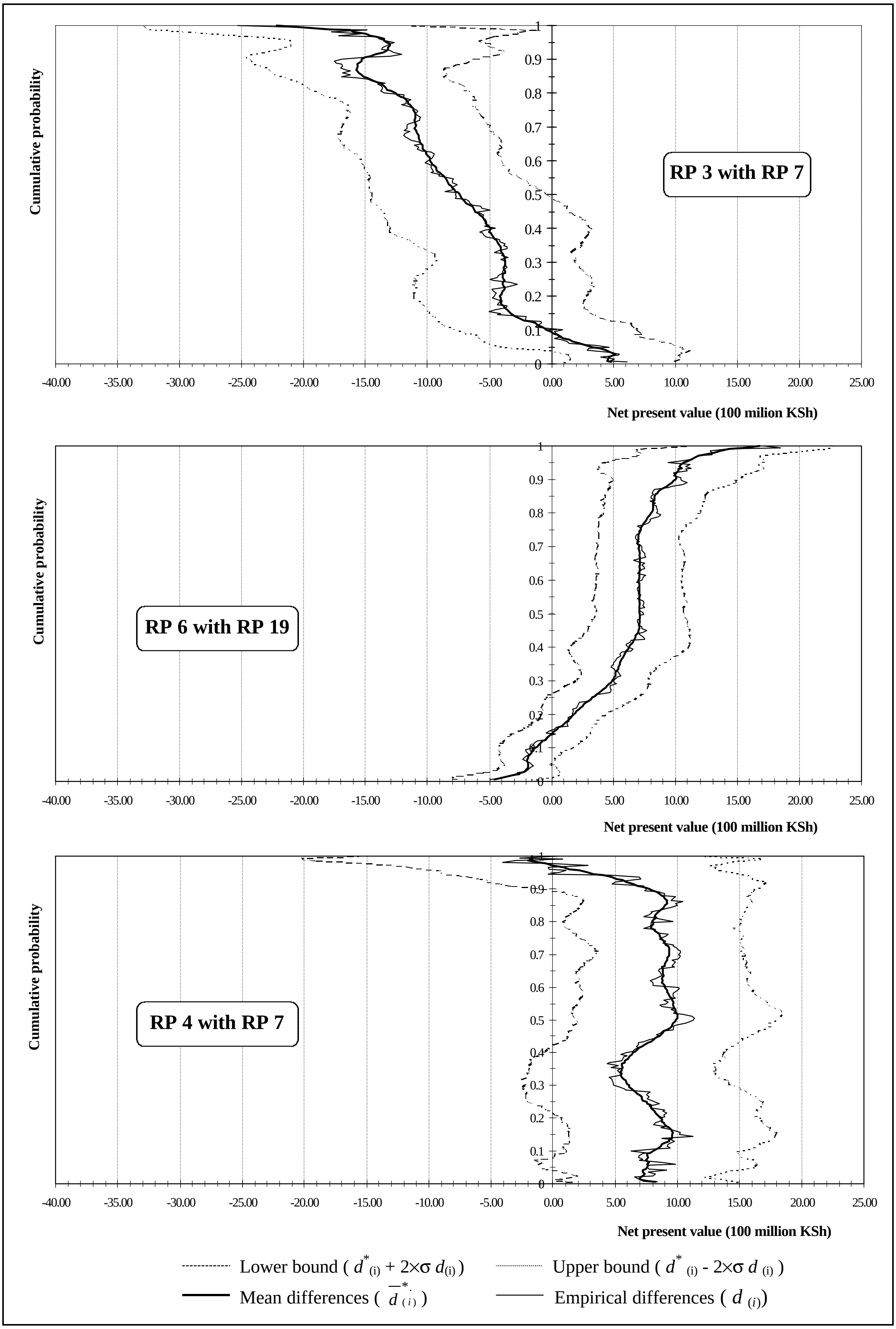
[9] Appendix *B* contains the inference statistics results for all remaining project pairs.

Figure 6-10: Confidence bands (α = 95 per cent) for the differences between the cumulative distribution functions (CDF) of selected project pairs



Here, it turns out that FSD is less robust since both CDFs may cross several times at the lower bound of the confidence interval. So, the confidence that RP 7 is dominant over RP 4 is somewhat less than 95 per cent. [10]

Table 6-10: Stochastic dominance results from bootstrap samples for selected dairy research projects

Project pair	From the original sample (FSD, B-RAC)	From bootstrap samples (FSD and B-RAC)		
		Lower bound	Mean	Upper bound
RP 3 vs. RP 4	-0.000000399	0.0005427465	-0.0000106844	-0.0006181830
RP 3 vs. RP 6	FSD	FSD	FSD	FSD
RP 3 vs. RP 7	0.000843435	0.002279193	0.000819531	0.0000537759
RP 3 vs. RP 19	FSD	FSD	FSD	FSD
RP 4 vs. RP 6	FSD	FSD	FSD	FSD
RP 7 vs. RP 4	FSD	0.000113466	FSD	FSD
RP 4 vs. RP 19	FSD	FSD	FSD	FSD
RP 6 vs. RP 7	FSD	FSD	FSD	FSD
RP 6 vs. RP 19	0.00175884	0.000534904	0.001785301	FSD
RP 7 vs. RP 19	FSD	FSD	FSD	FSD

Lower and upper bound define the confidence interval for the sample differences $d_{(i)}$ at a confidence level of 95 per cent;
B-RAC = break-even risk aversion coefficient;

FSD = First-order stochastic dominance.

This section has shown how bootstrap can be applied to test for the uncertainty associated with the estimated stochastic dominance relationships between research projects. On several occasions, it was found that the reliability of initial stochastic dominance results was not as high as to make clear statements regarding the rejection or approval of FSD of one project over another. Such unclear cases are not the exception, e.g., when decision alternatives have similar outcome distributions, which, in turn, underlines the usefulness of conducting inferential statistics in stochastic dominance analyses.

[10] Although the order statistics of the mean bootstrap differences between RP 4 and RP 7 cross the point $d_{(i)} = 0.00$ the "riskroot" program calculates FSD for RP 7 over RP 4. This must be due to the truncation procedure of the SD program that cuts off parts of the left-hand and right-hand tail of the CDF.

6.5 Stochastic Dominance Analysis for Multi-Attribute Decision Problems

Traditionally, the spread of stochastic dominance analysis has been largely restricted to decision making problems with only one objective (or attribute). However, likewise the priority setting exercise for dairy research in Kenya, practical decision making problems often require to consider risk and multiple objective simultaneously. The past work of multi-attribute utility (MAUT) theory (KEENEY and RAIFFA, 1976) suggest the use of a single synthetic criterion, but the application of this approach is greatly compromised by the necessity of obtaining complete information on the decision maker's preferences and the functional form of a multi-attribute utility function. It would be beneficial if stochastic dominance analysis could be amenable to multi-attribute situations without referring to an exact specification of a multi-attribute utility function. So, the analytical spectrum of stochastic dominance and the advantages it has over MAUT models could be broadened. Some work has been done on the theory of multi-attribute stochastic dominance (e.g., HUANG et al., 1978; MOSLER, 1982) but unfortunately the underlying conditions are quite complex and restrictive. Furthermore, decision analysts would have to develop their own stochastic dominance program since none of the existing software (e.g., riskroot or the GSDP program) is able to cope with multi-attribute problems.

This section describes the "synthetic outranking approach" developed by MARTEL and ZARAS (1995) that, if employed in conjunction with "ordinary" stochastic dominance analysis, allows the inclusion of multiple attributes. The approach will be illustrated by a decision making example including three-attributes. Results from the former stochastic dominance analysis with regard to uncertainty in the projects' net present values are taken to represent the efficiency attribute and these are combined with hypothetical SD results for the two other attributes. The "synthetic outranking approach" in conjunction with stochastic dominance follows a three step procedure:

- In step 1, stochastic dominance tests are conducted through pairwise comparisons of all decision alternatives with each attribute considered individually. These comparisons are interpreted in terms of partial preferences.
- In step 2, the synthetic outranking approach is employed by constructing outranking relations based on a "concordance" and "discordance" index. With this approach, a majority attribute condition (concordance test) replaces the unanimity condition of classic dominance.
- In step 3, these outranking relations are used to choose the best alternative or to rank a set of decision alternatives.

As a point of departure for the mathematical description of the synthetic outranking approach the following mathematical notion is introduced with the three important elements are as follows (MARTEL and ZARAS, 1995, p. 33):

- a set $A = \{a_1, a_2, ..., a_m\}$ representing the set of all feasible decision alternatives;
- a set $A = \{ X_1, X_2,...., X_n\}$, of attributes;
- an attribute X_i defined in the interval $[x_i^0, x_i^1]$ where x_i^0 is the worst value obtained with the attribute X_i and x_i^1 is the best value.

The synthetic outranking approach distinguishes two situations for the partial preferences (stochastic dominance results for a single attribute) between decision alternatives: "SD" identifies stochastic dominance situations consistent with the conditions imposed by the analysts. Depending on assumed risk preferences analysts define the type of stochastic dominance conditions to discriminate decision alternatives. If, for example, analysts consider only risk aversion to be relevant, a SD situation is established when FSD and SSD are fulfilled between the decision alternatives to be compared. Likewise $\overline{\text{SD}}$ designates those situations where one of the stochastic dominance FSD or SSD are not fulfilled.

In the $\overline{\text{SD}}$ case (incomparability case), elimination of a decision alternative is not possible and it will be necessary to make the decision maker's value system explicit by deriving his $U_i\,(x_i)$ function. In fact, two complexity levels are distinguished in the expression for the decision maker's preferences with respect to each attribute:

- clear – if the dominance conditions are fulfilled, i.e., the SD situation;
- unclear – if it is the $\overline{\text{SD}}$ situation.

It will be soon clear that a $\overline{\text{SD}}$ situation for one or more attributes does not inevitably lead to the need to specify the utility function but rather depends on the level of concordance threshold required by the decision maker in the construction of outranking relation. The lower the concordance threshold, the more $\overline{\text{SD}}$ situations can be accommodated. Given the desired level of concordance threshold, the value of the concordance index can be decomposed into "explicable" and "non-explicable" concordance (MARTEL and ZARAS, 1995, p. 36, 37). Explicable concordance results from the case in which the expression of the decision maker's preferences is trivial or clear:

(5) $$C_E\,(a_j, a_j^*) = \sum_{i=1}^{n} W_i\, d_i^E\,(a_j, a_j^*)$$

$$\text{where } d_i^E\,(a_j, a_j^*) = \begin{cases} 1 & \text{if } F_{ij} \text{ SD } F_{ij}^* \\ 0 & \text{otherwise.} \end{cases}$$

The a_j and a_j^* are two decision alternatives of the j th pairwise comparison. W_i is the relative importance given to the i th attribute, with $W_i \geq 0$ and $\sum W_i = 1$. F_{ij} and F_{IJ}^* are the CDF of the two decision alternatives a_j and a_j^* with respect to the i th attribute. The value of the explicable concordance can range between 0 and 1. If for example decision alternative a_j is dominant over alternative a_j^* by FSD (which leads to a SD situation) for every attribute, the value of the explicable concordance for a_j is 1 and for alternative a_j^* is zero. If FSD is found only for certain attributes then the value of the explicable concordance for both decision alternatives a_j and a_j^* ranges between 0 and 1.

The non-explicable concordance corresponds to the potential value of the cases in which the expression of the decision maker's preferences are unclear.

$$(6) \qquad C_N(a_j, a_j^*) = \sum_{i=1}^{n} W_i d_i^N(a_j, a_j^*)$$

$$\text{where } d_i^N(a_j, a_j^*) = \begin{cases} 1 & \text{if } F_{ij}\ \overline{\mathrm{SD}}\ F_{ij}^* \text{ and } F_{ij}^*\ \overline{\mathrm{SD}}\ F_{ij} \\ 0 & \text{otherwise.} \end{cases}$$

This second part of the concordance is only a potential value, as it is not certain that for each of these attributes F_{ij} will be at least as good as F_{ij}^*. Based on both concordance indices a condition can be derived for which attempts to make decision makers' preferences explicit is recommended.

(7) If the condition $0 \leq p - C_E(a_j, a_j^*) \leq C_N(a_j, a_j^*)$ is fulfilled,

where p denotes the concordance threshold, then the explanation of the unclear case with a $\overline{\mathrm{SD}}$ situation can lead to a value of the concordance index such that the concordance test is satisfied for the proposition that a_j globally outranks a_j^* (a_j S a_j^*). The discordance index for each attribute X_i is defined as the ratio of the difference between the means of the range of the scale (MARTEL and ZARAS (1995, p. 37):

$$(8) \qquad D_i(a_j, a_j^*) = \begin{cases} \dfrac{(\overline{F}_{ij}^* - \overline{F}_{ij})}{(x^1_i - x^0_i)} & \text{if } F_{ij}^* \text{ FSD}_i\ F_{ij} \\ 0 & \text{if } F_{ij}^* \text{ not FSD}_i\ F_{ij} \end{cases}$$

$\overline{F}^*_{ij}$ and $\overline{F}_{ij}$ are the mean values of the distributions a_j^* and a_j, and x^1_i and x^0_i are the highest and lowest values of the dominant distribution $\overline{F}^*$. The difference between the mean values of two distributions gives a good indication of the difference in performance of the two compared alternatives. If the difference is large enough (in relation to the range of the scale), and FSD is fulfilled on attribute X_i, then the chances are high that a_j is dominated by a_j^*. In that event, it should be assumed a minimum level v_i, called a veto threshold, of the discordance index giving to attribute X_i the power of withdrawing the credibility if this attribute is not in concordance with the proposition that a_j globally outranks a_j^*. The discordance test follows from the notion of a veto threshold v_i for each attribute. The concordance set (a) and discordance set (b) from the total set A can then be formulated as:

(9) (a) $\forall\, (a_j, a_j^*) \in A \times A, \qquad [(a_j, a_j') \in C_p \leftrightarrow C\,(a_j, a_j^*) \geq p]$

(b) $\forall\, (a_j, a_j^*) \in A \times A, \qquad [(a_j, a_j^*) \in D_v \leftrightarrow \exists_i \,/\, D_i\,(a_j, a_j^*) \geq v_i].$

The set of outrankings $S\,(p, v_i)$ can then be obtained from the intersection between the concordance set with the set complementary to the discordance set:

(10) $S\,(p, v_i) = C_p \cap \overline{D}_v.$

Next, depending on whether one is confronted with a choice or ranking statement, either the best alternative can be determined, or the outranking relations can be exploited to establish rank orders.

The approach of Martel and Zaras will be illustrated by a multi-attribute example for the set of the six top ranking dairy research projects with respect to net present value. The following assumptions are made: First, assume that decision makers have agreed on the three major attributes which are efficiency, equity and sustainability; further assume that all attributes are expressed in quantitative terms and outcome measures are represented through PDF and CDF.

For efficiency, we make use of the available stochastic dominance results with respect to net present value. For equity and sustainability, assume the hypothetical stochastic dominance relationships based on CDFs as outlined in Table 6-11. Another assumption must be included which is constant absolute risk aversion of the utility function (CARA). Risk aversion and CARA property requires for the discrimination of decision alternatives to pass first-order (FSD) and second-order (SSD) stochastic dominance tests. Thus, the clear and unclear cases can be stated as:

- clear situation (SD) – if FSD and SSD are fulfilled; and
- unclear situation $\overline{\text{SD}}$ – if one of the dominance conditions (FSD or SSD) are not fulfilled.

The stochastic dominance results for the three attributes are those presented in Table 6-11. Attributes weights were chosen as $W_{Efficiency} = 0.3$, $W_{Equity} = 0.3$ and $W_{Sustainability} = 0.4$. Further, we assume that the concordance threshold value p is 0.7 and the discordance (veto) threshold values v_i are all 0.3. SD results for efficiency are taken from Table 6-3. They are not stated in terms of B-RACs but, alternatively, in terms of FSD, SSD, or where B-RAC are positive in terms of $\overline{\mathrm{SD}}$.

Table 6-11: Stochastic dominance results for a multi-attribute decision problem

	Efficiency						Equity						Sustainability					
RP	**3**	**4**	**6**	**7**	**15**	**19**	**3**	**4**	**6**	**7**	**15**	**19**	**3**	**4**	**6**	**7**	**15**	**19**
3	*	**SSD**	**FSD**	$\overline{SD}$	**FSD**	**FSD**	*		**FSD**		**FSD**	**FSD**	*		**FSD**	**FSD**	**FSD**	**FSD**
4		*	**FSD**		**FSD**	**FSD**	**SSD**	*	**FSD**		**SSD**	**FSD**	**FSD**	*	**FSD**	**FSD**	**FSD**	**FSD**
6			*		$\overline{SD}$	$\overline{SD}$			*		**FSD**	**FSD**			*	**SSD**		
7	$\overline{SD}$	**FSD**	**FSD**	*	**FSD**	**FSD**	**FSD**	**FSD**	**FSD**	*	**FSD**	**FSD**				*		
15			$\overline{SD}$		*	$\overline{SD}$					*	**SSD**			**FSD**	**FSD**	*	**FSD**
19			$\overline{SD}$		$\overline{SD}$	*						*			**FSD**	**FSD**		*

Row alternative dominates column alternative

Table 6-11 shows that results for the efficiency attribute contains all three SD conditions with a relatively high incidence of unclear ($\overline{\mathrm{SD}}$) preferences. For simplicity, dominance relations for equity and sustainability were assumed to take either the FSD or SSD form, thus excluding unclear cases.

The explicable and the non-explicable concordance were calculated according to formula 5 and formula 6 for the set of alternative pairs (a_j, a_j^*) and are shown in Table 6-12. For the particular set of attribute weights, and the definition of clear and unclear cases all project pairs pass the concordance test (according to the condition formulated in (7)). This implies that, despite several unclear dominance cases found for efficiency, the proposition of global outranking of a_j over a_j^* given all three attributes holds true for a concordance threshold of 70 per cent ($p = 0.7$). Thus, elicitation of the utility functions is not necessary. Table 6-13 highlights the results of the discordance indices calculated according to formula 8.

Table 6-12: Explicable and non-explicable concordance indices

	Explicable concordance $C_E = C_{E\ (\mathrm{FSD+SSD})}$						Non-explicable concordance $C_N = C_{N\ (\mathrm{FSD+SSD})}$					
RP	**3**	**4**	**6**	**7**	**15**	**19**	**3**	**4**	**6**	**7**	**15**	**19**
3	*	0.3	1	0.4	1	1	*	0.0	0.0	0.0	0.0	0.0
4	0.7	*	1	0.4	1	1	0.0	*	0.0	0.0	0.0	0.0
6	0.0	0	*	0.4	0.3	0.3	0.0	0.0	*	0.0	0.3	0.3
7	0.6	0.6	0.6	*	0.6	0.6	0.3	0.0	0.0	*	0.0	0.0
15	0.0	0.0	0.7	0.4	*	0.7	0.0	0.0	0.3	0.0	*	0.3
19	0.0	0.0	0.7	0.4	0.3	*	0.0	0.0	0.3	0.0	0.3	*

$C_{E\ (\mathrm{FSD+SSD})}$ and $C_{N\ (\mathrm{FSD+SSD})}$ indicate that a clear situation (SD) is conditional on FSD and SSD relationships.

Row alternative dominates column alternative.

Table 6-13: Discordance indices

	Efficiency (v = 0.3)						Equity (v = 0.3)						Sustainability (v = 0.3)					
RP	**3**	**4**	**6**	**7**	**15**	**19**	**3**	**4**	**6**	**7**	**15**	**19**	**3**	**4**	**6**	**7**	**15**	**19**
3	*						*			0.41			*	0.19				
4		*		0.06				*		0.32				*				
6	0.39	0.32	*	0.37			0.38	0.45	*	0.51			0.35	0.53	*		0.36	0.22
7				*						*			0.23	0.15		*	0.26	0.17
15	0.35	0.39		0.34	*		0.31		0.24	0.44	*		0.44	0.63			*	
19	0.45	0.37		0.43		*	0.52	0.39	0.41	0.21		*	0.55	0.36			0.44	*

v is the discordance (veto) threshold value at 0.3 for all attributes.

For the concordance threshold of p = 0.7 and a veto threshold v_i = 0.3 for all i, the resulting concordance and discordance sets of research projects are:

$Q_{0.7}$ = {(3, 6), (3, 15), (3, 19), (4, 3), (4, 6), (4, 15), (4, 19), 15, 6), (15, 19), (19, 6)}

$D_{0.3}$ = {(4, 7), (6, 3), (6, 4), (15, 3), 19, 3), (19, 4)}.

Finally, the outranking set $S(p, v_i) = C_p \cap \overline{D}_v$ is:

$S_{(0.7, 0.3)}$ = {(3, 6), (3, 15), (3, 19), (4, 3), (4, 6), (4, 15), (4, 19), 15, 6), (15, 19), (19, 6)}

which is identical to the concordance set $Q_{0.7}$. Project ordering can be established by counting the number of stochastic dominance each project has over the others which leads to the following multi-attribute project ranking:

$$\{4\} \Rightarrow \{3\} \Rightarrow \{15\} \Rightarrow \{19\}.$$

The major advantage of the synthetic outranking approach is that it can be conducted with the same stochastic dominance programs that are used for single-attribute SD analysis. It embodies the clear advantage that one can circumvent the elicitation of a multi-attribute utility function, which is an onerous task even when the utility function is assumed to be additive and separable. The synthetic outranking approach is probably most suitable when the incidence of unclear cases $\overline{\text{SD}}$ is limited. However, for simplicity reason, this example has been manipulated in such a way that no problem occurs with the concordance test by first: choosing clear SD conditions for equity and sustainability, and second: by placing a relatively low attribute weight on efficiency that embodies several unclear $\overline{\text{SD}}$ cases. The failure of the synthetic outranking approach to generate unanimous ranking may be high and depends on the number of $\overline{\text{SD}}$ conditions, the structure of the attribute weights and the assumed concordance threshold. It can be easily demonstrated that increasing the efficiency weight from 0.3 to 0.4, for example, would induce the concordance test to fail several times.

A last comment concerns the question of whether synthetic outranking can be applied to the risk prone case. In fact, the adaptation of the synthetic outranking approach to risk proneness is straight forward. However, one additional problem is to define appropriate outranking conditions. Where FSD and SSD (and perhaps TSD) are sufficient to give clear indication of the dominance for risk aversion, risk proneness requires either positive FSD or a B-RAC which falls in the risk aversion interval (B-RAC > 0) together with the information on what alternative dominates below and above this B-RAC. Then, a clear statement can be made with respect to the dominance condition for risk prone decision makers. With this information one can substitute the risk averse conditions with the risk prone conditions of clear and unclear preferences in the concordance and discordance tests and can then proceed with the three working steps in a similar fashion.

6.6 Concluding Remarks on Monte Carlo Simulation and Stochastic Dominance

This chapter has given a first impression on available techniques for formal incorporation of risk and uncertainty in research investment analysis. Monte Carlo simulation and stochastic dominance analysis are two methods that cover two important tasks in priority setting, namely the quantification of the riskiness of individual research investments and decision support for research planning when the likely effects of research investments are not known for certain. These methods achieve this with virtually the same set of information that are needed for conventional methods, but require additional computational effort and well trained modellers and agricultural economists. A justification of the effort due to incorporating risk and uncertainty issues will always confront three major objections from the proponents of deterministic methods. The first is whether these rather demanding techniques are compatible with the limiting framework and scope of priority setting; the second is whether risk and risk attitudes really matter, and the third is whether quantitative risk analysis that suggests high precision is justifiable when underlying data and expert judgements contain a high degree of subjectivity. The answers to these questions will not always be the same but may differ among the large variety of priority setting exercises.

However, the need to consider risk and uncertainty is obvious: making projections into the future when doing ex-ante evaluation is always coupled with imperfect information, subjective expert opinions, and the uncertain economic and social environment. This is even more true for agricultural research in developing countries. As was argued earlier, ignoring risk and uncertainty would fail to give insights into the variations of research outcomes and, furthermore, would lead to the wrong impression that projected research impact will occur for certain. In several circumstances, deterministic models even embody the risk of wrong calculation of the expected gains from research especially when uncertain variables are correlated and linked multiplicatively.

If there is common sense on the importance of risk and uncertainty, numerical tools such as Monte Carlo simulation prove to be appropriate means to accounting for risk and uncertainty. Simulation provides detailed insights into sources of risk and how these sources affect the level and uncertainty of the final research outcome. Advanced scenario and sensitivity analyses in simulation programs even allow the exploration of the importance of various stochastic model variables and the effect they have on the uncertainty surrounding the outcome. The additional computational work becomes less of an argument when simulation is understood as a substitute for traditional sensitivity analyses found in deterministic models. So, some of the shortcomings of sensitivity analysis can be avoided.

A simulation model involves considerable work: model set-up, conducting multiple model runs, the management of large data sets and analysis and the communication of model results. So, it cannot be built in an ad-hoc fashion shortly before the beginning of a workshop but requires preliminary model preparation. Fortunately, the availability of new user-friendly simulation software offers a new perspective for the development of customised applications tailored to specific needs. So, much of the obstacle to using simulation in priority setting is already gone. Comparing research projects in a stochastic world requires alternative decision rules and criteria. Modellers should decide – depending on the time available and scope of a priority setting workshop – whether to compare projects based on expected values ignoring risk attitudes or based on stochastic dominance criteria. There is no convincing argument why project ranking should not be derived by stochastic dominance tests since SD software is easily accessible, tests are easy to apply, and the underlying assumptions regarding the utility function and risk preferences are rather soft.

7 A Stochastic Mathematical Programming Approach to Priority Setting

This chapter introduces mathematical programming approaches as decision aid under conditions of risk and uncertainty. So far mathematical programming and stochastic analysis of research investment choices have been studied separately with the application of a deterministic mathematical programming model in chapter 5 and with the stochastic dominance analysis in chapter 6. The purpose of this chapter is to integrate mathematical programming into a stochastic framework. This leads to the broad topic of portfolio choices under risk which has been a focus of interests for long time and has led to the development of a variety of so called "risk programming" techniques as a particular group in mathematical programming. Risk programming involves choices that have to be made as to the allocation of resources to some combination of risky prospects from among a set of all available risky prospects. Prominent fields of application are portfolio choices of financial assets and the selection of optimal production plans in agricultural farm business.

Risk programming introduced and applied to the case study complements planning and decision making in priority setting for agricultural research in significant ways by combining the advantages of mathematical programming with respect to the large spectrum of decision scenarios with the incorporation of the stochastic evaluation results from Monte Carlo simulation and the risk behaviour of decision makers. The main difference to stochastic dominance analysis is that the level at which evaluation and decision making under conditions of risk takes place is raised from the single research investment to a portfolio of many research investments.

This chapter is structured as follows: The first section is a brief outline of the decision theory with respect to multiple objectives under risk based on the "subjective expected utility" and its extension the "multi-attribute utility theory" (MAUT). Some important aspects are covered including e.g., the concept of multi-attribute utility and value functions, the different functional forms – additive and multiplicative – and the conditions for the validity of these functions. The next section concerns the application of two different risk programming models to a single-objective decision problem. Model results are the identification of a set of research portfolios each having a different degree of riskiness. In a further step, a multi-objective version of a risk programming model is employed to a 3-dimensional trade-off analysis between risk, efficiency and equity. Results are discussed in two different ways. First, one can examine the effect of changing attitudes towards risk on the trade-offs between efficiency and equity. Alternatively, one can look at the effects that changing weights on equity have on the trade-offs between risk and efficiency.

7.1 Theoretical Aspects of Multi-Attribute Decision Problems under Risk

To approach the multi-attribute decision problem, consider a complete set of feasible alternatives denoted by A and a particular alternative from this set denoted by a with each alternative being associated with a certain contribution to attributes $X_1,...,X_T$, denoted by $X_1(a)$, ..., $X_T(a)$. Then the decision maker's problem is to choose an alternative a in A so that he will be happiest with the payoff $X_1(a)$, ..., $X_T(a)$ which implies he wants to maximise the aggregate of the single payoffs. Thus, what is needed is first an index that combines $X_1(a)$, ..., $X_T(a)$ into a scalar index of preferability by specifying a value function V, and second, the functional type of combining the multiple attributes.[1] According to KEENEY and RAIFFA (1993, p. 68) a multi-attribute value function can be formally stated in its simplest form as:

(1) $$V(x_1, x_2,...,x_T) = V\{v_1(x_1), v_2(x_2),...,v_T(x_T)\} \qquad (\text{for } t = 1, 2, ..., T)$$

where v_i designates a value function over a single attribute X_i.

For the sake of facilitating the assessment of the multi-attribute value function, quasi-separability is often assumed. The essence of the quasi-separable value function is that instead of trying to assess the n-dimensional value function directly, it is only necessary to assess n one-dimensional value functions $v_i(x_i)$. This way the multi-attribute utility function is decomposed into component parts each of which is more readily handled. Quasi-separability requires that attributes are mutually preferentially independent.

The attributes X_i and X_j are jointly preferential independent of the other attributes if the location and shape of the decision makers' indifference curve for combinations of X_i and X_j are independent of the level of the other attributes. Given that mutually preferential independence holds for all attributes, the value function V (.) where $V(i)$ are scaled from zero is either of the additive or the multiplicative form (ANDERSON et al., 1977, p. 81-82). According to KEENEY and RAIFFA (1993, p. 111) the mathematical expression of the additive form can be stated as:

(2) $$V(x_1, x_2,...,x_T) = \sum_{t=1}^{T} k_t v_t(x_t) \qquad (\text{for } t = 1, 2, ..., T)$$

and of the multiplicative form as:

---

[1] A value function V (or sometimes called "ordinal utility function", "preference function", "worth function" or "utility function") is needed to compare the magnitude of the outcome X_i (a) and $X_j(a)$ because attributes X_i and X_j may be measured in totally different units. Thus an index is needed that combines the level or pay-off of the different objectives into a scalar index of preferability or value (KEENEY and RAIFFA, 1993, p. 68).

(3) $$V(x_1, x_2,...,x_T) = \prod_{t=1}^{T} (Kk_t v_t(x_t)+1)-1\}/K \qquad \text{(for } t = 1, 2, ..., T)$$

where k_t is a scaling factor between zero and one for $v_t(x_t)$ and
K is another scaling constant.

Because of the scaling requirements the k_t values determine K. If $\sum k_t = 1$, then K=0 and V takes the additive form. If $\sum k_t$ is not 1, then $K \neq 0$ and V takes the multiplicative form. The most popular approach in evaluating multidimensional consequences has been the additive value function. Its beauty lies in its relatively simple mathematics and computational convenience and can be justified in the absence of any information about the exact functional form. ANDERSON et al. (1977, p. 87) argue that though necessary conditions are rarely met, the assumptions of additivity may not be too bad since what is required of the multidimensional utility function is the power of discriminating between alternative prospects but less important is the accuracy of the total value of a prospect. Thus the additive form will generally serve reasonably well to discriminate between acts in much the same way as would a more correct but far more complicated non-additive function.

KEENEY (1971) has shown that attributes can be redefined to correct for a violation of the preferential independence assumption so that the additive form can be applied instead of other forms. A special case of the additive value function is when the single value functions are linear in x so that $v(x_t) = x_t$ and the total value is the simple weighted sum of the attribute measure (HARDAKER et al., 1997, p. 165):

(4) $$V(x_1, x_2,...,x_T) = \sum_{t=1}^{T} a_t(x_t)$$

where V is the multi-attribute value function and x_i is the attribute measure
corresponding to the i th attribute and a_i are scaling constants.

This functional form is the basis of many multi-attribute decision models and is most widely used in multi-objective programming and scoring models. However, the underlying assumptions under which multi-attribute utility functions can be reduced to this simple form are rarely, if ever, recognised.

So far, certainty has been assumed in the multi-attribute measures. Now the description of a decision problem will be extended to the case of uncertainty within which a single attribute measure is replaced by a probability distribution of attributes measures for a single attribute or multiple attributes. For the purpose of specifying a multi-attribute utility function with uncertainty, consider the simplest case where the utility function is quasi-separable and additive in its attributes. The operational form for a utility function can then be mathematically expressed as:[2]

(5) $$U(x_1, x_2,...,x_T) = \sum_{t=1}^{T} k_t \sum_{k=1}^{n} p_k u_t(x_{kt})$$

where $u_t(x_{kt})$ is the value of the utility function U_t for observation k given that U_t is a specific utility function for attribute t;

$\sum_{k=1}^{n} p_k u_t(x_{kt})$ is the expected utility for attribute t;

p_k is the probability of the k th state of nature for observation k over all attributes;

n is the number of observations; and

the constants k_t are scaling factors where $0 < k_t < 1$ and $\sum_{t=1}^{T} k_t = 1$.

This multi-attribute utility function results in the expected utility over all attributes since the utility values of the observations x_{kt} are weighted by their respective probability of occurrence. This additive model can be easily extended to a multiplicative model if the sum of the scaling factors k_t is set other than one. The mathematical expression of the multiplicative form can be found, e.g., in MEHREZ and SINUANY-STERN (1983, p. 432). In addition to preference independence, "utility independence" yet another assumption must hold for the decomposition of the multi-attribute utility function to be valid. An attribute X_i is said to be utility independent of the other attributes, if the decision makers' preferences for uncertain choices involving different levels of attribute X_i do not depend on the level of the other attributes. Utility independence is a stronger assumption than preference

[2] The majority of publications on decision making makes no clear distinction between the value function and utility function (e.g., ANDERSON et al., 1977, p. 80-82; HARDAKER et al., 1997, p. 161-166). But a distinction is helpful in keeping certainty and uncertainty conditions strictly apart. The value function (or preference function) $v(x)$ as used in the expected utility model of Bernoulli is measured in riskless conditions, encodes the strength of preferences of outcomes and explains why decision makers are risk averse. In the expected utility model of the von Neumann and Morgenstern type, the utility function $u(x)$ measures risky outcomes and can be interpreted as a probability indifference curve measured by means of lotteries (SMIDTS 1997, p. 359).

Preference and value functions have been linked recently through the concept of "intrinsic risk attitude" which states that an individual's preference for risky choice alternatives is a combination of the strength of preference for the outcomes and the attitude towards risk. Risk aversion as indicated by $u(x)$ is thus seen as the effect of diminishing marginal value indicated by $v(x)$ plus the aversion against the dispersion in subjective values indicated by $u(x)$. This implies that $u(x)$ is a transformation of $v(x)$ (SMIDTS 1997, p. 360).

The notion of intrinsic risk attitudes is very helpful in modelling multi-attribute decision making under risk. If a stable transformation function exists between $v(x)$ and $u(x)$ then a deterministic multi-attribute model with known $v(x)$ can be transformed into a model under risk with no – if $v(x)$ equals $u(x)$ – or only little effort to elicit $u(x)$. No clear empirical evidence exists of a functional relationship between $v(x)$ and $u(x)$ and, if a relationship is supported, of the functional form of that relationship. For further information, the reader is referred to SMIDTS (1997) and the numerous references cited there.

independence since it requires that the shape of the attribute utility function be independent of the level of the other attributes. Once a multi-attribute utility function has been specified in whatever form, it can be used in many types of analysis. If the multi-attribute utility function is defined for analysing resource allocation questions for certainty measures, a deterministic multi-objective mathematical programming model can be constructed and solved. If specified in uncertainty form, stochastic mathematical programming models can be constructed for multi-objective planning under uncertainty including the direct use of a linear- or non-linear multi-attribute objective function.

7.2 Mathematical Risk Programming Approaches

Risk programming models depict the risk inherent in model parameters. Risk considerations are usually incorporated assuming the risky parameter is known with certainty and is mostly represented as a probability distribution. Usually, the risk modeler's part becomes of finding an adequate representation of these probability distributions and of assessing the decision maker's response to parameter risk. An alternative way to the development of a risk model is to set up a deterministic linear programming model (LP), then, to solve it for every possible state of the risky parameter and choose one solution from the resultant plans. But such an approach suffers from dimensionality problems which manifest in the number of possible plans that arise when risk parameters and states of natures are numerous. A second issue is the certainty problems which McCARL (1997, p. 14-1) explains as follows: "*Every LP parameter is assumed known with perfect knowledge. Consequently, solutions reflect* "*certain*" *knowledge of the parameter values imposed. Thus, when one solves many models one gets many plans and the question remains which plan should be used*".

Risk programming models can be distinct in several ways. An important distinction is between cases where:

- all decisions must be made now with the uncertain outcomes resolved later; and
- some decisions are made now, then later some uncertainties are resolved followed by other decisions yet later.

These two frameworks lead to two very different types of models. The first model type is the most common and is generally known as "risk programming model" (HARDAKER et al., 1997, p. 181) and the second type is called "stochastic programming model", or according to McCARL (1997, p. 14-2) "stochastic programming model with recourse".[3] Another distinction is between risk models that incorporate risk in the objective function coefficients, technical coefficients or right-hand side separately or sometimes collectively. Methods of the first type are better developed and more widely used than methods of the other types. In the discussion that follows only risk in the objective function will be considered.[4]

7.2.1 Quadratic Risk Programming Models

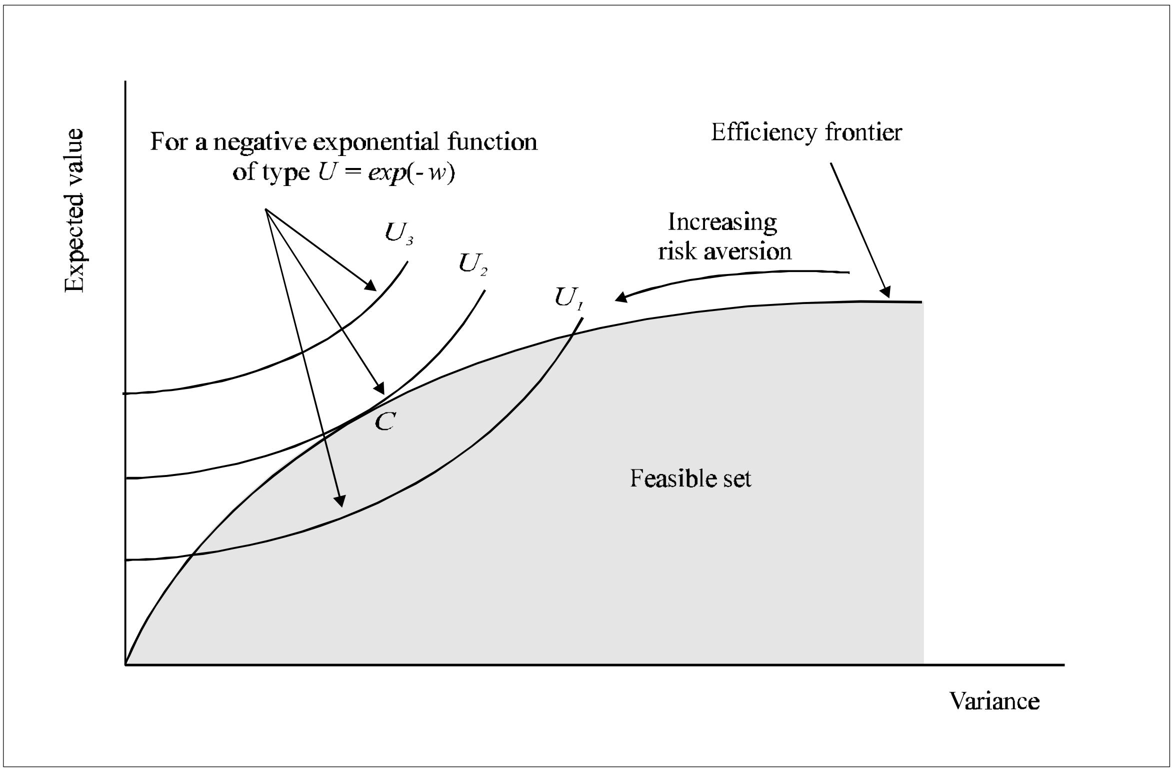
The most comprehensive method of accounting for risk in the objective function is that which uses quadratic risk programming (QRP). In this method a matrix is assembled representing the variance and covariance of the probability distribution of the risky parameter. This variance-covariance matrix is then attached to an initial activity matrix as would normally be used by standard LP, and the augmented matrix is solved by a quadratic programming algorithm. Quadratic risk programming uses the mean-variance or the E-V efficiency rule. The E-V rule is based on the proposition that if the expected value of prospect *A* is greater than or equal to that of prospect *B*, and the variance of *A* is smaller than or equal to the variance of *B*, with at least one strict inequality, then prospect *A* is preferred over prospect *B* by all decision makers that meet certain conditions. The conditions are that decision makers prefer more to less, and are risk averse in the sense that they trade-off gains in expected value of outcome against a reduction in variance. All those prospects, plans, or portfolios that are not dominated in an E-V sense can be regarded as members of an E-V efficiency set (HARDAKER et al., 1997, p. 141).

The E-V efficiency set can be depicted as in Figure 7-1 where the set of feasible solutions lies on or below the efficiency frontier and forms a convex set in the E-V space. The optimal solution point "*C*" on the E-V frontier can be found when the utility function is known and approximated in terms of E-V parameters. Several formulations have been proposed for solving a QRP model (MARKOWITZ, 1959; FREUND, 1956). Markowitz's original formulation of the E-V model minimised variance subject to a given level of expected income as in the multi-objective programming lexicographic formulation.

[3] It is outside the scope of this study to discuss both risk modelling types. Readers interested in stochastic programming models are referred to the textbooks by HARDAKER et al. (1997), RAE (1994), and the article by RAE (1971).

4 Again, readers interested in risk modelling of right-hand side and technical coefficients are referred to the textbooks by ANDERSON et al. (1977), HARDAKER et al. (1997), HAZELL and NORTON (1986), RAE (1994), and ROMERO and REHMAN (1989).

Figure 7-1: The E-V efficiency set of feasible solutions in E-V space



Source: Modified, after HARDAKER et al. (1997, p. 145.)

An alternative formulation is possible with the maximisation of expected income subject to a given level of variance. Freund's approach to E-V analysis treats E and V as a specific form of a weighted multi-objective programming model in which both – portfolio variance and expected value – are included in the objective function. This formulation can be mathematically expressed as:

(6) maximise $E(X) - F\ V(X)$

s.t. AX £ b and X ³ 0

$$E(X) = \sum_{j=1}^{m} c_j X_j \quad \text{and} \quad V(X) = \sum_{j=1}^{m} \sum_{k=1}^{m} X_j X_k s_{jk}$$

where X_j denotes the level of the j th activity;
c_j denotes the expected value of the j th activity;
s_{jk} denotes the covariance between the j th and k th activities
(s_{jk} will be the variance if $j = k$);
n is the number of activities;
A is a matrix of technical coefficients;
b is a vector of resource stock and
F is a risk aversion coefficient.

Here, the objective function maximises the expected value less the portfolio variance times a risk aversion coefficient F. The maximisation rule assumes that a decision maker will trade-off expected income for variance. The use of E-V models is a theoretically controversial subject due to the expected utility assumptions underlying the E-V rule. The major point of concern has been the conditions that must hold for the E-V rule to be equivalent to maximising expected utility. The conditions are that decision makers must have an outcome distribution that is normal, a utility function that is quadratic or risk that is small relative to the decision maker's initial wealth.

All these requirements can be regarded as highly questionable. Normal distributions are often the exception rather than the rule – e.g., prices and crop yields in agriculture may not be well approximated by a normal distribution (DAY,1965) and a quadratic utility function implies the unrealistic assumption of increasing risk aversion and small risk assumption is not met in all cases (BAILEY and BOISVERT, 1989). Therefore, as HARDAKER et al. (1997, p. 144) point out, the E-V criterion should be best regarded as an approximate rule. The portfolios generated from QRP models have the following stochastic dominance properties: if all the E-V conditions are met, the E-V efficiency frontier from QRP consists of portfolios that are dominant by second-order stochastic dominance (SSD) over all other portfolios off the frontier, while portfolios from the same E-V efficiency set cannot be discriminated by FSD and SSD. If conditions are not met QRP solutions are likely to violate the monotony axiom of the expected utility theory either because frontier solutions may be internally dominant by SSD – in this case there is clear preference among risk averse decision makers for portfolios dominant over others by SSD – or solutions off the frontier line could be members of the "true" frontier (HADAR and RUSSEL, 1969, p. 33; BAMBERG and TROST, 1996, p. 653).

7.2.2 MOTAD Models

Because computer routines for QRP were not widely available in the past and less highly developed than those for LP, several attempts were made to use LP approximations to the QRP approach.[5] Only Hazell's MOTAD model will be discussed here (HAZELL and NORTON, 1986) due to its extensive use and suitability for the research allocation problem. MOTAD is an acronym for Minimisation of Total Absolute Deviation. The method closely resembles QRP with the exception that risk is represented not as the sample variance but as the total absolute deviation from the mean (TAD). Another difference between the two model types is that in QRP the variance-covariance coefficients are directly incorporated into the model, while in MOTAD programming the stochastic returns are represented by a

[5] See for example HAZELL (1971); THOMAS et al. (1972); CHEN and BAKER (1976). A critical review on the fallacy of MOTAD models can be found in MCCARL and TICE (1982).

set of vectors of activity return deviations. As with QRP several formulations are possible either as maximisation of expected returns subject to a given level of TAD, as minimisation of TAD subject to minimum expected return or as a composite objective function including expected returns, TAD and a risk aversion coefficient simultaneously. The mathematical expression of the objective function and deviation constraint for the "composite" variant of the MOTAD formulation can be stated as:

(7) maximise $$\sum_{j=1}^{m} \overline{c_j} X_j - y \sum_{k=1}^{n} (d_k^+ + d_k^-)$$

$$\text{s.t. } \sum_{j=1}^{m} (c_{kj} - \overline{c_j}) X_j - d_k^+ + d_k^- = 0 \text{ for all } k$$

where d_k^+ and d_k^- are the deviations of the k th state of activity return;

c_{jk} is the per unit return of activity X_j at the k th state of nature (observations);

m is the number of activities;

n is the number of state of observations;

$\overline{c_j}$ is the mean of activity X_j and

y is a risk aversion coefficient.

The advantages of MOTAD models are that they can be solved by standard LP solver and use the structure of an input-output tableau as LP and QRP models, but need to be augmented with additional constraints for the calculation of the mean absolute deviations. The major disadvantage is that MOTAD does not have a direct link to the expected utility theory. Consequently, MOTAD solutions are even less likely to be utility efficient than those given by QRP. TAUER (1983) developed a different version of the MOTAD model known as Target MOTAD which overcomes some the theoretical limitations through the specification of a target level on total return while allowing deviations from the target. The major advantage is that solutions are dominant by second-degree stochastic dominance regardless of the distribution of activity returns and so are efficient for risk averse decision makers.[6]

7.2.3 Risk Programming Models Based on Maximisation of Expected Utility

In view of the shortcomings of QRP and MOTAD models LAMBERT and MCCARL (1985) introduced the "Direct Expected Maximising Non-linear Programming" formulation (DEMP) which maximises the expected utility of wealth. DEMP was designed as a direct

[6] A detailed description of MOTAD and target MOTAD models can be found in MCCARL (1997) and HAZELL and NORTON (1986)

alternative to QRP which is free of restrictions on the forms of the utility function and free of assumptions regarding the distribution of the uncertain parameters. Since then, Lambert's and McCarl's model has been widely acknowledged and constantly refined. This has been made possible by the availability of large scale non-linear programming software such as GAMS in combination with MINOS or the Premium Solver for MS EXCEL.[7] KAYLEN et al. (1987) employed a variation of DEMP where the probability distributions are of a known continuous form and numerical integration is used in the solution. The DEMP model has also been applied by LAMBERT and MCCARL (1985), LAMBERT and MCCARL (1989), FEATHERSTONE et al. (1988), and RAFSNIDER et al. (1993). The basic DEMP formulation for a research portfolio problem requires specification of a utility function *U*, and the probability distribution of the objective function parameters including research projects' return (NPV or CBR) and the probability of occurrence. Expressed in mathematical terms, the objective function of a DEMP model can be described as (MCCARL 1997, Chapter 14, p. 15):

(8) maximise $$E(U) = \sum_{k=1}^{n} p_k U\left(\sum_{j=1}^{m} Z_{jk} X_j\right)$$

s.t. *AX £ B* and *X ³ 0*

where Z_{jk} is the return per unit of productive activity *j* for observation *k*;

X_j is the absolute level of activity *j*; *m* is the number of possible activities;

$U(\sum_{j=1}^{m} Z_{jk}X_j)$ is the value of the utility function for the portfolio of activities for observation *k* given a specific utility function *U*;

p_k is the probability of the *k* th state of nature for observation *k*;

n is the number of observations;

A is a *l* by *m* matrix of technical coefficients with *l* denoting the number of restrictions;

X is a *m* by 1 vector of activity level and

B is a *l* by 1 vector of resource stock.

To change a linear programming model into the utility formulation one needs only construct a new objective function in which the original activity returns are replaced by utility values through the specification of a utility function. Then, if the utility function is monotone and concave for a risk averter, a good solver should be able to find the global optimum. However, the model is limited to risk aversion since risk proneness implies a convex utility function for which it is hard to find the global optimum. A direct link between QRP and

[7] The Premium Solver Add-In for Microsoft EXCEL is a commercial software package developed and distributed by Frontline Systems Inc. This solver is not identical with the standard solver Add-In.

DEMP models exists – this means both generate identical results and can be applied interchangeably – if the utility function is of the negative exponential type and portfolio returns are normally distributed. FREUND (1956) as cited in ANDERSON and DILLON (1992, p. 57) has shown that maximising expected utility can then be alternatively expressed in terms of mean and variance using a Taylor series expansion around the mean and can be solved via QRP with the following objective function:

(9) maximise $E[(U)x] = E(x) - F\ V(x)$ *with* $F = ½\ r_{(a)}x$

and where F is one-half of the Pratt-Arrow absolute risk aversion coefficient $r_a(x)$.[8] The maximisation of expected utility $E[(U)x]$ is then nothing else but the maximisation of the certainty equivalent. The method of direct utility maximisation is clearly superior to all other approaches since it perfectly fits with the EU hypothesis. However, in the standard form it can only be applied if decision makers have the same risk preference and the utility function is known. For situations when this is not the case, PATTEN et al. (1988) have developed an analytical procedure called "Utility Efficient Programming"(UEP) using assumptions akin to those used for the generalised stochastic dominance concept.

In UEP models the utility function is defined for a measure of risk aversion $r_a(x)$ and the type of risk aversion such as CARA, DARA or IARA. Then $r_a(x)$ is varied over a certain range and a solution set is generated that is stochastically dominant for all decision makers whose $r_a(x)$ is in the relevant range. Arguments for the superiority of UEP over DEMP are the same as for those of GSD compared to the use of a single utility function. If the model user decides for a one-step DEMP optimisation given a specific utility function, model results are specific to this particular setting while the scope for generalisation is very small. In contrast, an UEP model with, say a CARA utility function, and applied over a range of $r_a(x)$ is strategically equivalent to any other UEP model whose utility function belong to the same family and risk aversion range. This way, the arbitrariness of the utility function regarding scale and origin is eliminated and results are much more open for generalisation.

For this purpose SAHA (1993) proposed a special functional form which he called "expo-power" utility function (EP function) that has the advantage of determining decreasing, constant or increasing relative and absolute risk aversion depending on the estimated values of its parameters (formula 10). The major advantage of this function, if incorporated into an objective function of an UEP model, is that the effect of alternative assumptions regarding increasing, decreasing or constant risk aversion, changing preferences towards risks

[8] Which is equivalent to the absolute risk aversion coefficient $r_a(x)$ in chapter 6.

(changes in $r_a(x)$), and the use of the absolute or relative Pratt-Arrow risk aversion coefficient, on optimum decisions can be studied simply by changing the function’s parameter values rather than by replacing one utility form with another one. The "expo-power" function takes the following functional form:

(10) $U(x) = q - exp(-bx^a)$

where U denotes utility, *exp* denotes exponential, and x is wealth. The parameter restrictions of the utility function are $q > 1$, a ¹ 0, b ¹ 0, and $ab > 0$. From function (10) the Pratt-Arrow coefficient of absolute $r_a(x)$ and relative risk $r_r(x)$ aversions are given by (SAHA, 1993, p. 906):

(11) $$r_a(x) = -\frac{u''(x)}{u'(x)} = \frac{1 - a + ab\ x^a}{x}$$ and

(12) $$r_r(x) = -\frac{xu''(x)}{u'(x)} = 1 - a + ab\ x^a$$

Under its parameter restrictions, the "expo-power" function exhibits decreasing absolute risk aversion (DARA) if $a < 1$, constant absolute risk aversion (CARA) if $a = 1$, and increasing absolute risk aversion if $a < 1$. By changing parameters b, decreasing relative risk aversion (DRRA) is given if $b < 0$, and increasing relative risk aversion (IRRA) if $b > 0$. The "expo-power" function is quasi concave for all $x > 0$, and the necessary condition for (strict) concavity is given by $a - abx^a - 1$ (<) ≤ 0 and the sufficient condition is given by a (<)≤ 1. Because the EP function is unique up to an affine transformation, parameter q does not play a role in the characterisation of risk attitudes or in determination of optimal choices (SAHA, 1993, p. 906).[9]

DEMP and UEP models usually have a non-linear objective function. The degree of non-linearity depends on the non-linearity of the utility function. A linear utility function would lead to a linear problem, a quadratic utility function to a quadratic problem and an exponential utility function would lead to an objective function which is the weighted sum

[9] For the purpose of risk programming models some properties of the EP need to be commented. First, the EP function is unique up to an affine transformation, and therefore conforms to the relevant von Neumann-Morgenstern axiom of expected utility representation. Second, the alternative risk preference structures with the EP function nests, and the degree of non-linearity, are fully characterised by the value of parameters a and b. Third, although EP nests DARA, CARA, and IARA, it encompasses only IRRA and DRRA, and not constant relative risk aversion (CRRA), as special cases. Third, since EP is globally quasi-concave, optimisation of the expected EP function subject to a set of constraints will lead to global optimum (SAHA 1993, p. 906).

of the state of nature utility values from exponential utility functions. UEP and DEMP models can alternatively be formulated and solved by linear segmentation of the utility function using "separable programming" techniques as explained e.g., in DULOY and NORTON (1975), HAZELL and NORTON (1986), and GÜDER and MORRIS (1988). But the use of a separable programming algorithm may result in large problems. Depending on the solver at hand, it adds at least one row for each return observation and one column for each separable grid point for each observation.[10] While the increase in size may be tolerable, separable programming techniques have their limitation when applied to a UEP problem with varying risk preferences due to the need to modify the slope parameter of the linear segments at each new level of $r_r(x)$.

7.3 Application of Utility Efficient Programming and Quadratic Risk Programming to Research Portfolio Analysis

This section describes the analysis of the research portfolio problem for the dairy case study with explicit consideration of uncertainty and decision makers' risk preferences. The major questions to be studied are what alternative choice options decision makers have and how susceptible these choice options are towards risk preference changes. Other important aspects are the implications of alternative risk portfolios on the trade-off between efficiency and risk reduction. Furthermore, given the extra complexity of risk models, a final set of questions will address the potential gains from risk modelling from better decisions and the applicability of the different approaches in priority setting. A second type of analysis is aimed at the direct comparison of UEP models with QRP models and tries to examine the major differences of the resultant research portfolios. Much of previous studies on risk modelling have undertaken a comparative analysis (e.g., HARDAKER and TRONCOSO, 1979; RAFSNIDER et al., 1993; TEW et al., 1992) and have used different approaches simultaneously in order to add empirical evidence to the theoretical discussion on the suitability of these risk programming models. Here, the comparative study will be limited to UEP and QRP models.

7.3.1 Model Structure of the Utility Efficient and Quadratic Risk Programming Models

The evaluation of an optimal research portfolio for the 19 different project types begins first with the development of the UEP model. The layout of the UEP tableau is shown in Figure

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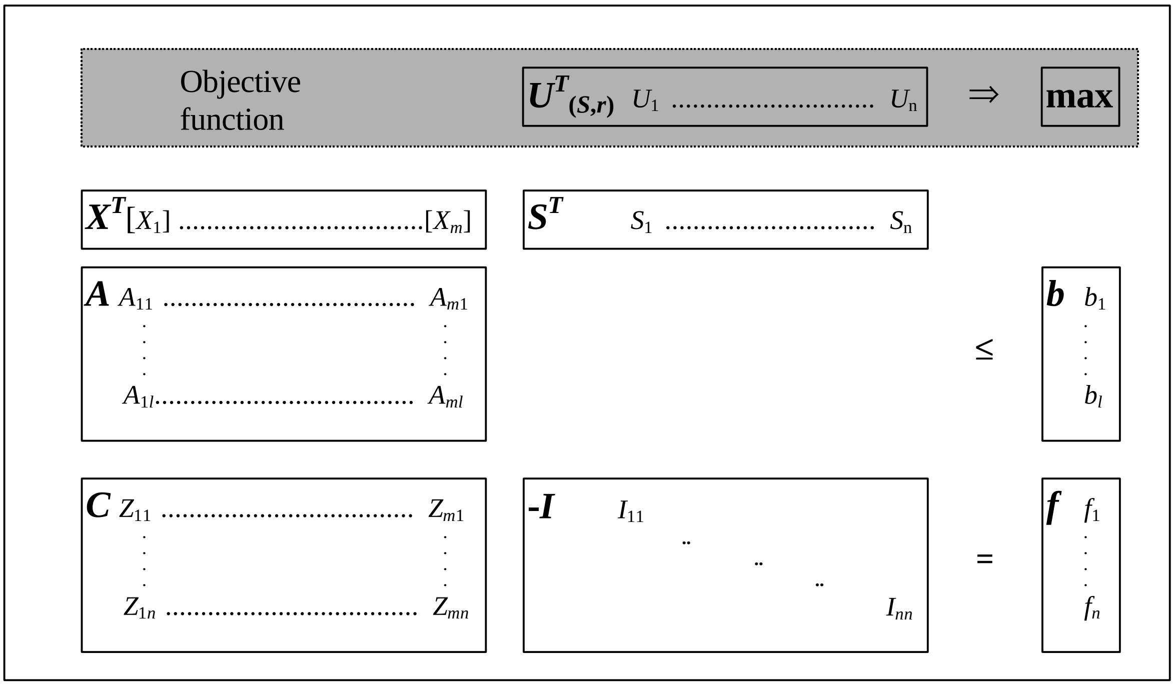
[10] For example, 200 NPV observations delineated into 10 grid point would add 2000 columns and 20 rows. This would be a significant large addition in the LP model.

7-2. For the particular case study matrix C contains all projects' net present value observations; for example Z_{11}, ..., Z_{1n} are the simulated 200 net present values for the first project activity X_1. Each state of nature (observation) k is then aggregated over all projects j through matrix I in which all diagonal elements take the value 1. For example, element I_{11} aggregates the individual projects' net present value Z_{11}, ..., Z_{m1} to the net present value of a research portfolio for the first state of nature, and I_{22} for the second state of nature. Vector f represents initial wealth or NPV for each state of nature k and will be assumed to be the same across all states. Because the dairy research program is looked at in isolation from all other research activities at KARI, no account will be made of external research impacts except that of dairy. Therefore, initial wealth is assumed to be zero. Vector X^T represents the project activity levels X_j whose values are restricted to [0; 1] integer values.

Figure 7-2: Outline of an utility efficient programming tableau



X_1, ..., X_m are [0; 1] decision variables representing research projects;

A_{11}, ..., A_{ml} are technical coefficients for resource use, etc.;

Z_{11}, ..., Z_{mn} are coefficients of the projects' return (e.g., NPV or CBR) with n observations for each project;

I_{11}, ..., I_{nn} are diagonal elements to calculate the return of a portfolio;

S_1, ..., S_n are summation variables representing the net present value of a research portfolio for each state of nature;

U_1, ..., U_n are summation variables representing the utility of a research portfolio for each state of nature;

b_1, ..., b_l are right-hand side coefficients representing resource availability and other constraints;

f_1, ...f_n represent initial wealth.

Source: Modified, after HARDAKER et al. (1997, p. 195)

Furthermore, all 200 observations are equally likely to occur as is generally the case with observations generated from a simulation model. Therefore, individual probability values p_k as included in formula 3 can be reduced simply to $1/n$ or can be omitted in the UEP tableau. If probabilities differ they need to be included as a vector P composed of the elements p_1, .., p_n leading to utility values U_1, ..., U_n in the objective function weighted by their probability of occurrence p_1, .., p_n. Vector S^T summarises portfolio NPVs for each state of nature depending on the portfolio composition. Vector $U^T_{(S,r)}$ translates the NPVs into utility values for a defined utility function specified by $r_a(x)$. The sum or the expected value of the portfolios' utility values will then be subject to maximisation. Matrix A contains the technical coefficients and vector b represents resource stock. [11]

For the analysis ahead, the UEP model starts with a simple example and imposes only one restriction which is budget availability. The technical coefficients in A are undiscounted research costs and b is the total undiscounted budget available. The utility function chosen is one of the "expo-power" function type as in described in formula 10:

$$(13) \qquad U(x) = [q - exp(-b\, x^a)] \times s$$

and a is set equal to 1 in order to induce CARA property for the utility function. A minor modification is the coefficient s which is needed as a scaling factor for the utility differences.[12] Risk aversion levels are selected to range from 0 to 0.001[13] within which the break-even risk aversion coefficients B-RAC for pairs of research portfolios are approximated iteratively. Model runs are done for several budget levels – which is the only restriction of the resource stock – ranging from 10 to around 60 million KSh.

For the formulation of the quadratic risk programming model, a variance-covariance matrix of the NPVs is calculated and related to the activity level. The composite objective function consists of the mean return and variance as well as of a risk aversion coefficient F which is

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[11] The outline of the UEP tableau as shown here is an example of a structural form developed for "older generation" MS-DOS based solver tools. The major shortcoming is that this form tends to mushroom in size since the dimension of the objective function and number of columns is directly proportional to the number of the states of nature n caused by the transfer matrix I. Modern solver engines offer special functions that significantly reduce the size of a UEP model (e.g., the Premium solver for MS-EXCEL).

[12] The coefficient s neither affects the value of $r_r(x)$ nor the optimal solution. The scaling problem in UEP models arises for high levels of $r_r(x)$ when utility differences between two portfolios converge to zero due to increasing concavity of the utility function. The scaling problem adds considerable inconvenience to parametric variation of $r_r(x)$ since the scaling factor s needs to be adjusted frequently. If not scaled properly non-linear solver return "non-feasible solution" or, even worse, may generate utility-inferior solutions.

[13] Risk aversion intervals are set smaller than for the SD analysis in chapter 6. This is due to the scaling problem cited above which creates difficulties for optimisation when $r_r(x)$ is set above a value of 0.0003.

parametrically changed including risk averse and risk preferring attitudes. The layout of the QRP model is as outlined in Figure 7-3. Matrix Q represents the quadratic m by m variance-covariance matrix. The total portfolio variance (V) can thus be calculated by multiplying the variance-covariance matrix with the activity vector such as $V = X^{T} QX$. The elements of vector $\overline{C}$ are the expected NPVs of the 19 research projects and by multiplying $\overline{C}$ with X yields the expected value of the research portfolio.

Figure 7-3: Outline of a quadratic risk programming tableau

Objective function

$\boldsymbol{X^T}$ $[X_1]$ ....$[X_m]$ $\quad \overline{C}X - \Phi\, X^TQX \quad \Rightarrow \quad$ **max**

$\overline{C}$ $\quad \overline{c}_1$ .... $\overline{c}_m$

$$\boldsymbol{A}\ \begin{matrix} A_{11} & \cdots & A_{m1} \\ \vdots & & \vdots \\ A_{1l} & \cdots & A_{ml} \end{matrix} \quad \leq \quad \boldsymbol{b}\ \begin{matrix} b_1 \\ \vdots \\ b_l \end{matrix}$$

$$\boldsymbol{Q}\ \begin{matrix} Z_{11} & \cdots & Z_{m1} \\ \vdots & & \vdots \\ Z_{1m} & \cdots & Z_{mm} \end{matrix} \qquad \boldsymbol{X}\ \begin{matrix} [X_1] \\ \vdots \\ [X_m] \end{matrix}$$

$X_1, \ldots, X_m$ are [0; 1] decision variables representing research projects;

$\overline{c}_1, \ldots, \overline{c}_m$ are the expected value of the projects' net present value distributions;

$A_{11}, \ldots, A_{ml}$ are technical coefficients for resource use, etc.;

$Z_{11}, \ldots, Z_{mm}$ are variance (diagonal elements) and covariance coefficients (non-diagonal elements) of the net present value distributions; and

$b_1, \ldots, b_l$ are right-hand side coefficients representing resource availability and other constraints.

Source: Modified after HARDAKER et al. (1997, p. 187)

7.3.2 Risk Modelling Results

Table 7-1 highlights the results from the UEP model. Risk portfolios were calculated for 8 different budget levels. Initially, budget levels were increased in decimal steps from 10 to 60 million KSh. But as some steps did not yield alternative plans, other budget levels close to initial values were chosen instead. So, for each budget level an alternative research plan to the initial risk neutral portfolio exists. This implies that risk averse decision makers can increase their expected utility if they opt for the alternative risk plan. Table 7-1 outlines the risk efficient research portfolios generated from the UEP model for selected budget levels. Each budget level has two portfolios, the first is the risk neutral portfolio, and the second is the alternative portfolio that is preferred by risk averse decision makers separated by a B-RAC value below which the risk neutral portfolio is dominant and above which the risk averse portfolio is dominant. As can be seen from Table 7-1 this has its costs in terms of a reduction in NPV. Therefore, risk averse decision makers would scarify some of the portfolio NPV for the sake of risk reduction. The low B-RAC values indicate that choice options are not the consequence of an unrealistically high degree of risk aversion. If labelled with a subjective risk attitude B-RAC values would represent risk neutrality or modest risk aversion which may cover the majority of the research management's risk preferences.

Table 7-1: UEP research portfolios for risk averse decision makers

		Research project type																			Mean net present value	Budget used
Budget restriction	B-RAC*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	KSh million	KSh million
12 KSh (mil.)				■	■			■				■									43,332.42	11.89
	0.000575			■				■			■	■	■							■	41,745,60	11.77
19 KSh (mil.)				■	■			■			■	■	■						■	■	58,774.61	18.91
	0.000696			■	■			■				■	■	■					■	■	58,599.00	18.81
23 KSh (mil.)				■	■			■		■		■	■						■	■	62,371.24	22.86
	0.000464			■	■			■			■	■	■	■	■				■	■	62,151.93	22.72
28 KSh (mil.)				■	■			■	■	■	■	■	■	■					■	■	67,680.68	27.68
	0.000861			■	■	■	■	■			■	■	■	■					■	■	67,214.11	27.53
43 KSh (mil.)				■	■		■	■		■	■	■	■	■		■			■	■	79,330.57	41.77
	0.000183			■	■		■	■	■	■	■	■	■	■	■		■		■	■	79,104.84	42.99
45 KSh (mil.)				■	■		■	■		■	■	■	■		■	■			■	■	80,760.48	44.71
	0.000661			■	■		■	■	■	■	■	■	■	■	■		■		■	■	80,254.02	43.54
52 KSh (mil.)				■	■		■	■	■	■	■	■	■	■		■	■		■	■	85,346.67	51.42
	0.000395			■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	85,045.96	50.48
54 KSh (mil.)				■	■		■	■	■	■		■	■		■	■	■		■	■	85,627.27	53.81
	0.000727		■	■	■		■	■	■	■	■	■	■	■	■	■			■	■	85,316.32	53.34

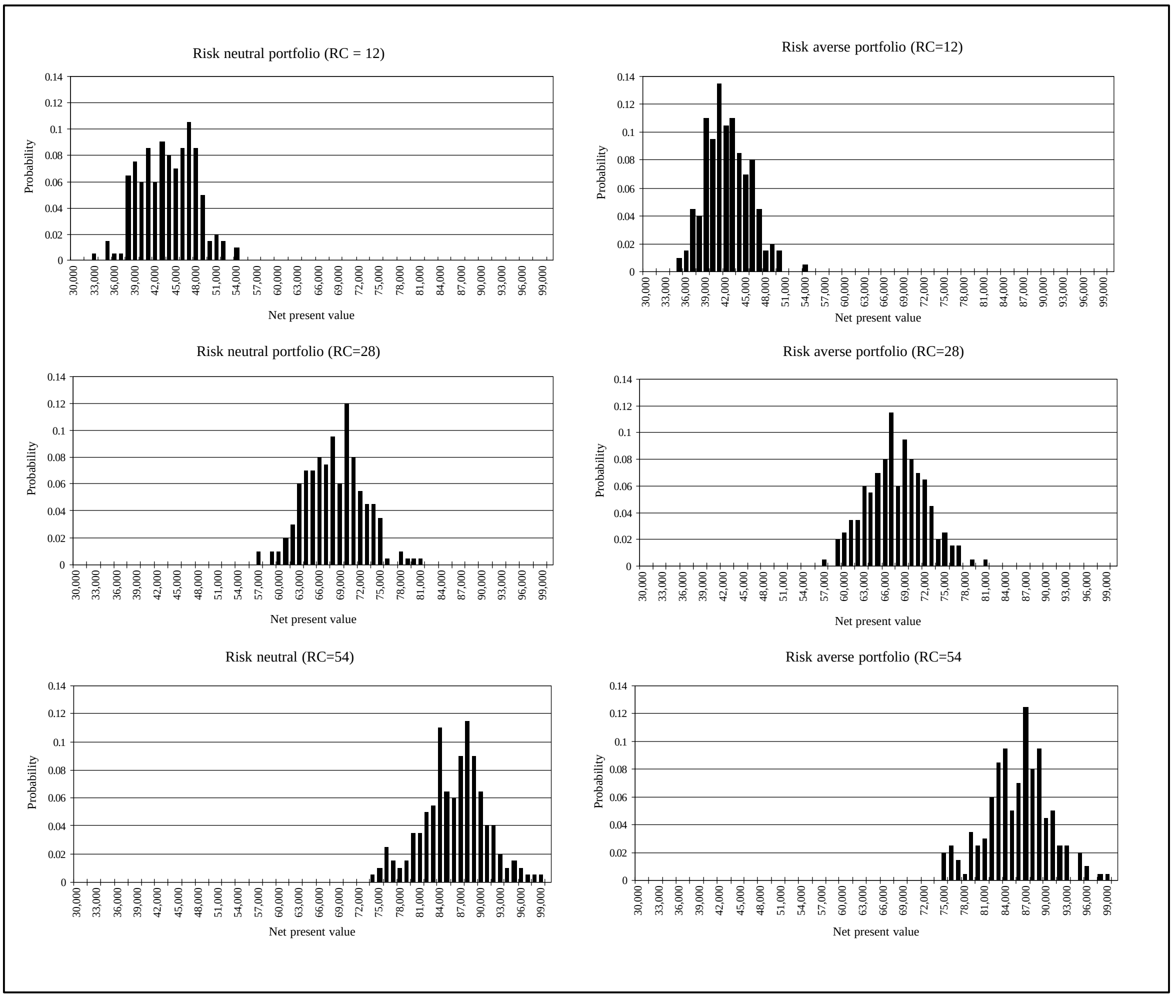
* The first research portfolio (risk neutral) at any budget level is dominant by GSD over the second portfolio between 0 and the B-RAC value. Above the B-RAC value the risk averse research portfolio dominates the risk neutral portfolio.

B-RAC is the break-even risk aversion coefficient.

Proposed research projects are indicated by dark shaded squares. Those not in the solution are left blank.

Adjustment in the composition of a research portfolio is realised in different ways. Take as an example the two portfolios at the 19 million budget level. The difference between the two portfolios is just the substitution of project type 13: "appropriate calf housing", by project type 10: "practical mastitis control", while all other projects remain unchanged. These two projects are known to break-even at -0.0179598 (see Table 6-4, chapter 6) with project 13 being the more risky type. Portfolio alternatives of this type could be readily forecast by taking the B-RAC results from the SD analysis although this does not always guarantee success. Potential projects that may substitute each other are characterised by the presence of a B-RAC and similar research costs. However, all other portfolio alternatives from Table 7-1, e.g. for the 45 million budget level, do not resolve that simply since portfolio adjustments occur at several places.

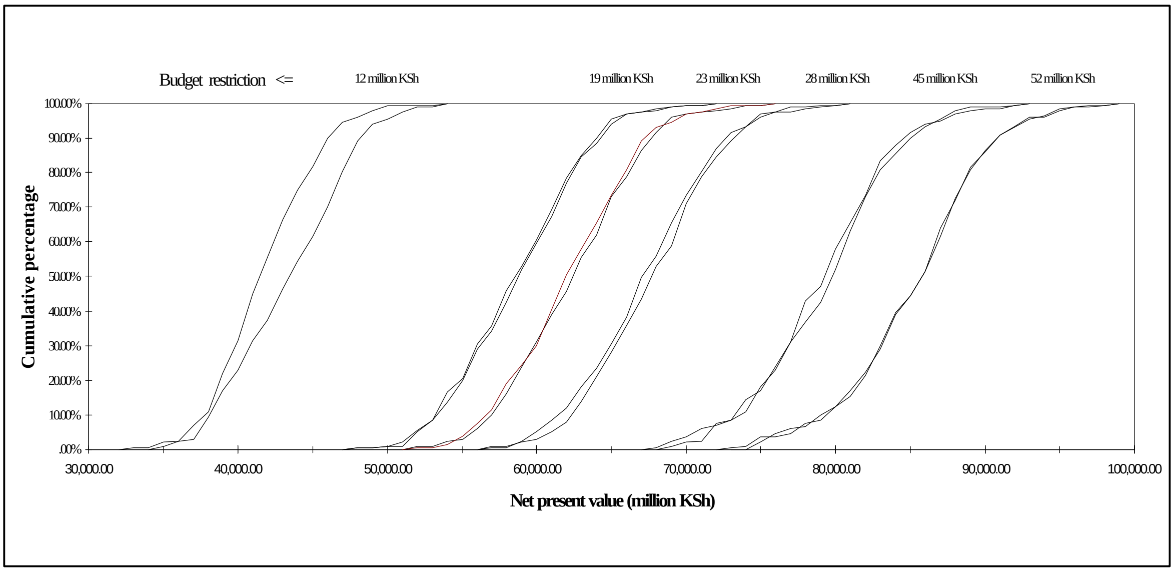
Figure 7-4: Density functions of selected utility efficient research portfolios



RC denotes research costs in million KSh.

A particularly important example is where one project – mostly a larger one in terms of NPV – is substituted by a group of several smaller projects: e.g., for the 12 million budget level the high ranking project type 4: "forage production and utilisation" is replaced by a group of three smaller projects; namely project 10, 12 and 19. In all these cases a pre-assessment based on stochastic dominance results would not be not possible. Thus, assembling an optimum research portfolio at a given risk level needs to be done by means of a risk programming model.

Figure 7-5: Cumulative distributions of selected utility efficient research portfolios



RC denotes research costs in million KSh

Another finding is the robustness of the solutions which means that only one alternative plan exists within each budget group. These relatively few choice options have several reasons. First, UEP models generate a limited set of solutions that are stochastically dominant by SSD over non-member solutions but are internally not SSD which implies that cumulative distributions cross at least one time (see Figure 7-4). The second reason is that the [0;1] integer formulation takes away a large part of the variability that normally continuous variables in a risk model have. Other reasons are the relatively small number of projects, the uneven NPV structure as well as the small range of the examined risk averse interval.

In the next step, results form the quadratic risk programming model which are summarised in Table 7-2 are examined and compared with those from the UEP model. A general finding is that the QRP model offers, for all 6 different budget levels, a much broader variety of alternative plans than the UEP model.

Table 7-2: Research portfolios from quadratic risk programming for risk averse decision makers

		Research project type																			Mean net present value	Variance	Budget used
Budget restriction	F	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19			
12 KSh (mil)	0			■	■			■				■									43,332	16.1E+6	11.89
•	0.0003			■				■			■	■	■							■	41,745	10.8E+6	11.77
	0.0006			■							■	■	■	■					■	■	34,936	6.0E+6	11.41
	0.009								■		■	■	■	■					■	■	26,100	2.6E+6	11.99
19 KSh (mil.)	0			■	■			■			■	■	■						■	■	58,774	17.5E+6	18.91
	0.00024			■	■		■	■				■	■								53.442	13.2E+6	18.998
	0.0005			■				■	■		■	■	■						■	■	49,939	11.2E+6	18.68
	0.0007			■			■				■	■	■	■					■	■	42,276	6.9E+6	18.08
23 KSh (mil.)	0			■	■			■		■		■	■						■	■	62,371	18.1E+6	22.86
•	0.0002			■	■			■			■	■	■	■	■				■	■	62,151	17.7E+6	22.72
	0.0043			■			■	■			■	■	■	■					■	■	55,066	12.3E+6	21.96
	0.0008			■			■		■		■	■	■	■					■	■	45,463	7.1E+6	21.91
28 KSh (mil.)	0			■	■			■	■	■	■	■	■	■					■	■	67,680	18.4E+6	27.68
	0.006			■		■	■	■	■		■	■	■	■					■	■	58,378	12.4E+6	27.30
	0.0008			■		■	■		■	■	■	■	■	■					■	■	50,334	8.2E+6	27.91
	0.0010			■			■		■		■	■	■	■			■		■	■	48,292	7.4E+6	27.73
	0.0012						■		■		■	■	■	■	■		■		■	■	38,673	4.6E+6	27.85
43 KSh (mil.)	0			■	■		■	■		■	■	■	■	■		■			■	■	79,330	21.2E+6	41.77
•	0.0001			■	■		■	■	■	■	■	■	■	■	■		■		■	■	79,104	20.3E+6	42.99
	0.0005			■		■	■	■	■	■	■	■	■	■	■		■		■	■	68,357	14.3E+6	40.98
	0.0007			■		■	■		■	■	■	■	■	■	■	■			■	■	60,234	10.4E+6	42.54
52 KSh (mil.)	0			■	■		■	■	■	■	■	■	■	■		■	■		■	■	85,346	21.9E+6	51.42
•	0.0002			■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	85,045	21.2E+6	50.48
	0.0006			■	■		■		■	■	■	■	■	■	■	■	■		■	■	74,960	15.6E+6	50.91
	0.0008		■	■			■		■	■	■	■	■	■	■	■	■		■	■	63,334	10.7E+6	51.21
	0.0010	■		■		■	■		■	■	■	■	■	■	■	■	■		■	■	63,191	10.6E+6	51.82

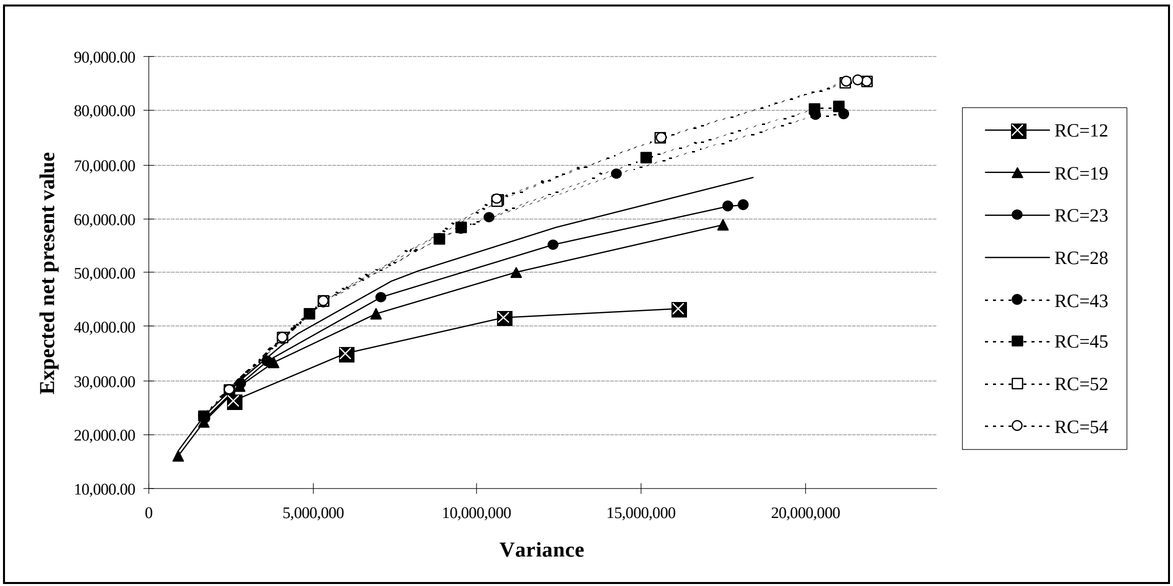
The weighting factor F denotes the risk aversion coefficient. F was varied between 0 and 0.02

The small dot "•" marks utility efficient portfolios that are identical with the UEP model.

Table 7-2 presents only a small fraction of the complete set of solutions, dropping those plans that leave a large share of the budget idle. The plans are ordered in sequence of increasing risk aversion as indicated by the increase in F. The trade-offs between efficiency and risk are manifest in the decrease of the portfolio NPVs in conjunction with a reduction in variance. These trade-offs can be looked at in more detail from Figure 7-6 which plots the QRP portfolios in the E-V space as members of the efficiency frontiers.[14]

[14] For clarity, efficiency frontiers in Figure 7-6 are shown as lines with all solutions connected. This suggests that a infinite number of solutions exists on the frontier which is not true for mixed-integer and binary programming models.

Figure 7-6: Expected value-variance (E-V) efficiency frontiers for quadratic risk programming research portfolios and risk aversion

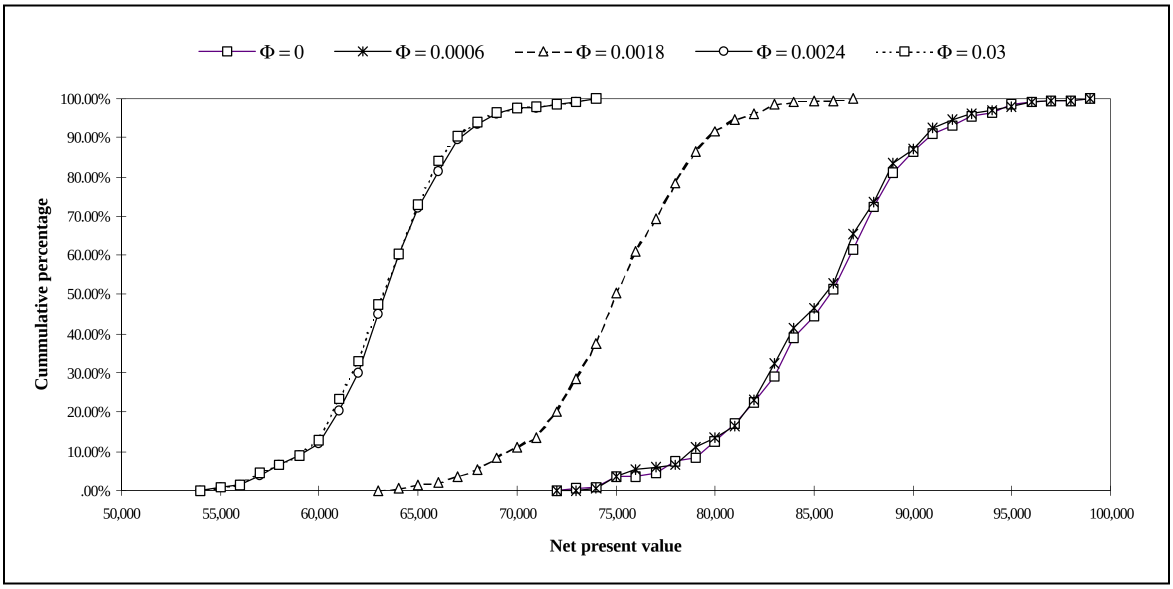


RC denotes research costs in million KSh

Inspection of Figure 7-6 also reveals that for any budget level the E-V efficiency frontier has a concave shape and the efficiency-risk trade-off acquires more strength when moving from risk neutrality to risk aversion. Probably the most important finding is that for the majority of the solutions, it cannot be said that they are real alternatives according to the expected utility theory because clear preference structure can be found. Preferences exist between the risk neutral solution and the alternative risk averse plans as well as between risk averse plans at various F levels in terms of SSD and FSD. This becomes obvious especially for FSD cases when the cumulative probability distributions of these plans as presented in Figure 7-7 are examined.

Another shortcoming is that risk efficient solutions found by the UEP model are not automatically found by QRP model. The violation of the expected utility theorem and the generation of inferior solutions is much more likely to occur for high level risk aversion as can be seen in Figure 7-7. The fact that QRP does not show a similar pattern to UEP model results is rather surprising because, at first sight, the conditions for QRP to comply with the EU theorem seem to hold fairly well. Most of the NPV distributions of the 19 projects are approximately normally distributed, which is supported by the test statistics reported in Table 6-3. Even if the normality condition of the NPV distribution of a single project does not hold, the NPV distribution of the portfolio (which is a function of many NPV distributions) should be expected to approach normality when the number of projects are numerous.

Figure 7-7: Cumulative distributions of selected quadratic risk programming portfolios (budget available: 52 million KSh)



In the next step QRP is used to extend risk analysis to the risk preferring case. Unlike the vast number of risk analysis studies documented in the literature, it is hard to find any study that has undertaken risk analysis for risk preferring cases. There are two major reasons for this. One is that empirical studies on farmer's attitude toward risk have unambiguously supported risk aversion. Another reason is that activity diversification – the portfolio involves a mixture of risky prospects – only takes place if the decision maker is risk averse since diversification always reduces variability unless prospects are not perfectly correlated. On the other hand the optimal strategy of a risk preferrer is total specialisation and his optimal portfolio will always consists of one single prospect. This uni-prospect solution is neither interesting from the analyst's perspective nor has great practical relevance for planning in agriculture.

However, the formulation of the risk portfolio problem for this case study is somewhat different. Apart from the scientific endeavour a few good reasons exists why the extension of risk analysis to risk preferring can be justified. First, the phenomenon of specialisation into a single activity only holds for continuous variables but not for binary variables of an investment activity. Consequently, the solution set is made up of a diverse set of activities. Second, there is a lack of information regarding research institutions' risk preferences, so one cannot exclude the possibility that they might be inclined to follow a risky strategy under certain circumstances, e.g., when they are faced with the decision to invest in risky bio-technology or conventional research. Table 7-3 below presents the QRP results for risk preferring decision makers. The risk coefficient F is set to vary between 0 and 0.05. Note that the objective function is now a function of the mean net present value plus the risk term implying that loss in efficiency is not traded-off against risk (variance) reduction but against risk (variance) increase. Accordingly, the objective function takes the form:

(14) $E(X) + F\ V(X)$

s.t. *AX £ B* and *X ³ 0*

Table 7-3: Research portfolios from quadratic risk programming for risk proneness

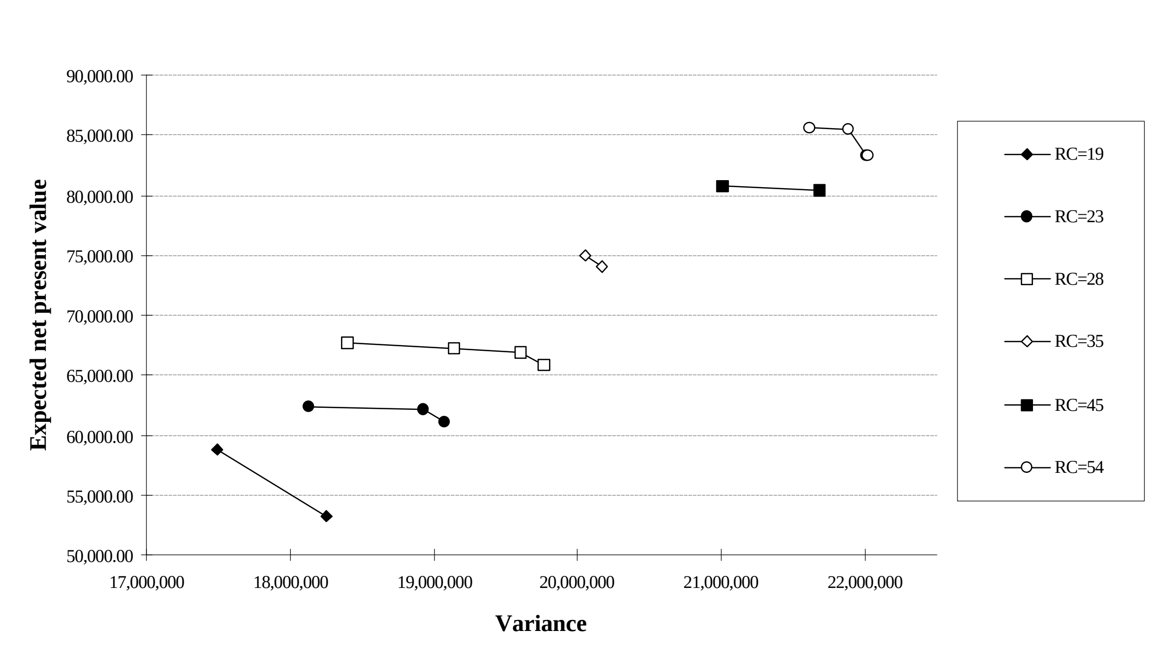
Budget restriction	Φ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Mean net present value	Variance	Budget used
12 KSh (mil.)	0			■	■			■				■									43,332	16.1E+6	11.896
19 KSh (mil.)	0			■	■			■			■	■	■						■	■	58,774	17.5E+6	18.91
	0.0073			■	■		■	■				■	■								53,183	18.2E+6	18.88
23 KSh (mil.)	0			■	■			■		■		■	■						■	■	62,371	18.1E+6	22.86
	0.00032			■	■		■	■			■	■	■	■						■	62,081	18.9E+6	22.95
	0.0053			■	■		■	■			■	■	■							■	61,107	19.0E+6	22.51
28 KSh (mil.)	0			■	■			■	■	■	■	■	■	■					■	■	67,680	18.4E+6	27.68
•	0.00065			■	■	■	■	■			■	■	■	■					■	■	67,213	19.1E+6	27.53
	0.00086			■	■		■	■		■	■	■	■	■						■	66,827	19.6E+6	27.44
	0.0053			■	■		■	■		■	■	■	■							■	65,853	19.7E+6	27.01
35 KSh (mil.)	0			■	■		■	■	■	■	■	■	■	■					■	■	75,020	20.0E+6	34.36
	0.0074			■	■		■	■	■	■	■	■	■						■	■	74,047	20.1E+6	33.92
43 KSh (mil.)	0			■	■		■	■		■	■	■	■	■	■	■			■	■	79,330	21.1E+6	41.77
	0.0074			■	■	■	■	■		■	■	■	■			■			■	■	78,482	21.2E+6	42.84
45 KSh (mil.)	0			■	■		■	■		■	■	■	■		■	■			■	■	80,760	21.0E+6	44.71
	0.00056			■	■		■	■	■	■		■	■			■			■	■	80,393	21.6E+6	44.62
52 KSh (mil.)	0			■	■		■	■	■	■	■	■	■	■		■	■		■	■	85,346	21.8E+6	51.42
	0.001			■	■		■	■	■	■	■	■	■			■	■		■	■	84,372	21.9E+6	50.98
•	0.019			■	■	■	■	■	■	■		■	■			■	■		■	■	83,349	22.0E+6	51.94
54 KSh (mil.)	0			■	■		■	■	■	■		■	■		■	■	■		■	■	85,627	21.6E+6	53.81
	0.00043			■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	85,472	21.8E+6	52.92
•	0.014	■		■	■		■	■	■	■		■	■			■	■		■	■	83,351	22.0E+6	53.91
•	0.016			■	■	■	■	■	■	■		■	■			■	■		■	■	83,349	22.0E+6	51.94

Weighting factor *F* denotes the risk aversion coefficient and is varied between 0 and 0.05.

The small dot "•" marks solutions that are utility efficient.

An examination of the structure of the expected values and variances of the research project's NPV can serve as a first indication of how QRP results for risk averse and risk preferring decision makers might develop. Other findings are similar to those described above for risk averse analysis. Among the member solutions, a few are utility efficient – at the modest risk preferring interval – while the majority in the strong risk prone interval is not risk efficient, as it can be studied from Table 7-3.

Figure 7-8: Expected value-variance (E-V) efficiency frontiers for quadratic risk programming (QRP) research portfolios and risk proneness



Correlation is another issue which seems to play an important role for the analysis of the risk preferring case. Although no effort was made to induce correlation among the final NPV distribution of the research projects, some negative correlation seems to have occurred at random.[15] Research projects with negative correlation can reduce the total portfolio variance if included and can increase variance if removed. Table 7-3 shows several examples of this phenomenon. For example, some of the alternative risk preferring plans under budget restrictions 23, 28, 35 and 52 million KSh have been derived simply by the removal of a single project whose NPV distribution is negatively correlated to the rest of the portfolio distribution.

However, non-efficient solutions are much closer in terms of NPV and variance, see for example the E-V diagram in Figure 7-8, and utility efficiency cannot be elaborated without a formal SD analysis. Another similarity with the risk aversion analysis is the changing degree of the trade-offs between risk and efficiency. In both cases the degree of conflict between risk and efficiency increases when moving away from risk neutrality.

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[15] Positive correlation was induced only among net yield increase distributions for different AEZs (see chapter 4, Table 4-2, but not for the final project NPV. The final NPV distribution of each research project has been calculated with a different and uncorrelated set of random numbers.

7.4 The Economic Gains from Risk Modelling

So far, much has been said about the technical details of risk programming, and intensive use was made of such programming approaches to examine alternative research plans under different risk conditions for the dairy case study. Now, the focus of this section is more on the economic aspect of risk modelling by addressing two important issues. The first is whether explicit consideration of risk improves decision making, and if so, how can this be expressed in terms of a monetary value.

The second issue is how much better is decision making when based on UEP solutions compared to QRP solutions given that the accuracy of QRP is not always met. The gains from risk modelling will be approached by comparing decision makers' options provided by a deterministic model with the options identified by a risk model. The underlying assumptions are that first: decision makers act rationally and choose only the best plan, and second: decision makers' risk preferences are known a priori with certainty. Alternatively, when preferences are unknown or there is a group of decision makers, gains need to be assessed over a certain risk range.

A variety of methods for doing this have been suggested. One method has been proposed by MORGAN and HENRION (1990, p. 308 ff.), which they called "the expected value of including uncertainty" (EVIU). The EVIU concept calculates the expected value of the difference in loss or utility between an optimal decision ignoring risk and the Bayes decision.[16] But EVIU requires considerable analytical effort and will not be used here. A simpler method has been purposed by PULLEY (1981) who simply uses the ratio of the utility of the E-V portfolio *EU*(*E-V*) to the direct utility maximisation portfolio *EU*(*UE*). This measure expresses the percentage of maximum utility captured by the E-V approximation. As a ratio it is invariant to scale transformation of the utility function but is sensitive to additive utility constants. Another index was suggested by KROLL et al. (1984) which is defined as:

(15) $$I_{KLM} = \frac{EU(E-V) - EU_n(UE)}{EU(UE) - EU_n(UE)}$$

where $EU_n(UE)$ is the expected utility of a "naive" equally weighted portfolio. The I_{KLM} index uses the "naive" portfolio (or deterministic portfolio) as a reference point to measure the gains in utility of an E-V portfolio relative to the gains in utility of a utility maximisation

[16] Interested readers are referred to MORGAN and HENRION (1990, Chapter 12) and the references cited there.

portfolio. The advantage of I_{KLM} is its invariance with respect to both scaling and additive transformation of the utility function. An alternative method is the certainty-equivalent index (CEI) recently proposed by REID and TEW (1986). It has the form:

(16) $$CEI_{RT} = \frac{CE(E-V)}{CE(UE)}$$

where CE(.) is the certainty equivalent which the individual would value equally with the return distribution of the selected portfolio.[17] This index gives the certain monetary value (e.g., KSh) of the E-V portfolio as a proportion of the CE of the utility maximising portfolio. Therefore, it is invariant to linear transformations of the utility function. As the ratio of two certainty equivalents, it has a straight-forward economic interpretation, thus, the CEI_{RT} index will be used for the subsequent analysis. More precisely, the reciprocal of the CEI_{RT} is taken in order to calculate not the losses but the gains from using the superior methods (see the formulas in Table 7-4). Results are summarised in Table 7-4 and comprise 11 different risk aversion levels and 2 different budget levels.

The results on the left-hand side of Table 7-4 underline that gains from risk modelling are rather insignificant. For example, at low levels of risk aversion – below the B-RAC of the first alternative risk portfolio – differences in certainty equivalent are zero because no portfolio change is recommended. But even above B-RAC risk portfolios perform only 2 per cent better at a 19 million KSh budget level and respectively 0.5 per cent at a 43 million KSh budget level than the deterministic portfolio. For other budget levels not analysed results may be similar.

An interesting point to observe is that when moving further in risk averse direction CE differences decline and finally disappear. This is attributable to the increasing concavity of the utility functions when $r_a(x)$ becomes larger which leads to utility differences approaching zero. The right-hand side of Table 7-4 reports the gains from using UEP instead of QRP portfolios, defined as the percentage certainty equivalent difference between UEP and QRP. Take the E-V and UE portfolios with the 19 million budget as an example. Starting from a low risk aversion level until the B-RAC of the first E-V alternative portfolio given at $r_a(x)$ = 0.0005 (or Φ = 0.00024), no differences exit because UEP and E-V criterion suggest the

[17] According to KEENEY and RAIFFA (1993, p. 143) a certainty equivalent of a lottery L with the uncertain consequences $\tilde{x}$ is an amount $\hat{x}$ such that the decision maker is indifferent between L and the amount $\hat{x}$ for certain and $\hat{x}$ can be defined as $u(\hat{x}) = E[u(\tilde{x})]$ or $\hat{x} = u^{-1}Eu(\tilde{x})$. Thus, the certainty equivalent can be calculated by taking the inverse of the utility function at the expected value of utility. For the "expo-power" utility function $u(x) = [q - exp(-b\ x)] \times s$ the inverse function is $u^{-1}(x) = -\ ln\ (q - x/s) \times 1/b$.

same portfolio. At risk levels between $r_a(x)$ =0.0005 and 0.0009 the UEP portfolio is superior to the E-V portfolio with a maximum level of 12 per cent KSh CE.

Table 7-4: The economic gains from risk modelling

	Gains from risk modelling using the UEP model				Gains from using the UE model instead of the QRP model			
Measurement criteria	$CEI = \frac{CE(EU)}{CE(EU_n)}$	$CEI_{\%} = \frac{CE(EU) - CE(EU_n)}{CE(EU_n)} \times 100$			$CEI = \frac{CE(UE)}{CE(E-V)}$	$CEI_{\%} = \frac{CE(UE) - CE(E-V)}{CE(E-V)} \times 100$		
Budget available	19 million KSh		43 million KSh		19 million KSh		43 million KSh	
$r_a(x)$	*CEI*	*CEI%*	*CEI*	*CEI%*	*CEI*	*CEI%*	*CEI*	*CEI%*
0.0001	0	*0*	0	*0*	0	*0*	0	*0*
0.0002	0	*0*	1.0004	*0.0408*	0	*0*	0	*0*
0.0003	0	*0*	1.0029	*0.2945*	0	*0*	0	*0*
0.0004	0	*0*	1.0051	*0.5097*	0	*0*	0	*0*
0.0005	0	*0*	1.0003	*0.0027*	1.1179	*11.7866*	0	*0*
0.0006	0	*0*	0	*0*	1.1073	*10.7298*	0	*0*
0.0007	1.0026	*0.2642*	0	*0*	1.0210	*2.1028*	0	*0*
0.0008	1.0204	*2.037*	0	*0*	1..0001	*0.0134*	0	*0*
0.0009	1.0058	*0.5813*	0	*0*	1.0337	*3.3742*	0	*0*
0.0010	0	*0*	0	*0*	1.2158	*21.5762*	1,1484	*14.8356*
0.0011	0	*0*	0	*0*	1.0431	*4.3146*	1.0480	*4.7967*

$CE(EU_n)$ denotes the certainty equivalent of the risk neutral (or deterministic) portfolio.

In order to make risk preferences between UE and QRP comparable, the risk aversion coefficients F from QRP are assumed to be equivalent to ½ $r_a(w)$, see formula (4), section 7.1.3.

The UEP model identifies the risk neutral portfolio as the best choice while the QRP model suggests an alternative portfolio at F = 0.00024 that is stochastically inferior. Utility differences then continuously decline and disappear until $r_a(x)$ approach 0.0009. At $r_a(x)$ = 0.0009 a new UEP portfolio is introduced (at a B-RAC of 0.000896) which leads to a rise in CE differences of around 3.5 per cent. At $r_a(x)$ = 0.001 and above, CE differences reach a new peak at 22 per cent due to the introduction of the second QRP portfolio at Φ =0.0005. Here again the second QRP portfolio is not stochastically efficient and has a much lower CE than the correspondent UEP portfolio.

To summarise some of the major findings, solutions from the UEP model are in many cases superior to those from the QRP model but never inferior. The degree of superiority depends very much on the risk preference examined and cannot be predicted intuitively. QRP results are reliable at low levels of $r_a(x)$ but the drop in quality may be considerable under extreme risk preferences in both directions. Concerning the gains from risk modelling, these gains are always positive which implies that risk modelling cannot perform worse than a deterministic model. Gains in the case study are not very high and do not vary much along the risk space.

7.5 Comparison of Risk Programming Techniques for Practical Applications in Priority Setting

As demonstrated in this chapter there are a number of ways of formulating risk models. Two of them have been applied and have shown remarkable differences. The UEP model provides a very small but utility efficient set of alternative portfolio choices. Some people may see the lack of portfolio choices as a weakness and may argue that UEP models are not the best alternative for risk modelling. But the quality of a risk model should not be judged by the number of solutions; more important is the quality of solutions which should be manifest mainly on decision theoretic grounds. Undoubtedly, the UEP model is superior in situations where conditions of the E-V assumptions are not met (e.g., normal distribution, IARA, and almost risk neutral preferences).

However, the low variability in alternative portfolios is very specific to the case study at hand and can be traced back to the small number of projects and the [0; 1] integer formulation of the model. Greater variability can be expected with more projects, with a more homogenous structure of project returns or with the lifting of the [0; 1] restriction. With respect to the latter issue one could adopt the ALSTON et al. (1995, p. 450 ff.) model formulation in which project returns and costs are defined in terms of a continuous research response function or in terms of discrete finite project sizes with varying costs and returns. To decide for Alston’s approach crucially depends on the possibility of eliciting those cost-return relationships which is by no means an easy task. On the contrary, the QRP model offers a much greater variety of choices but many of the choices are sub-optimal.

Care is always needed when results are to be discussed with and presented to decision makers. Model users should therefore try to filter utility efficient from non-efficient solutions which can be done eventually in an intuitive way by comparing NPV and variances of the portfolios, by plotting the cumulative and density distributions or can be resolved in a formal way by using GSD tests. A useful first step is always the examination of the distribution type of the final returns. If the distributions of the projects' net present value are approximately normal one can expect that QRP and UEP models yield similar results and, thus, QRP model results can be treated with more confidence. But as it was shown in our example, testing for normal distribution can be misleading as well.

Another independent line of comment relates to the possibility of risk portfolio analysis for other than the efficiency objective and other risk sources. So far, risk programming has dealt with incorporating uncertainty inherent in potential yield increase that has lead to a distribution of financial return in terms of NPV. But there is no limitation to apply a risk programming model to any other risky parameter or objective. Risk programming can handle a broad range of interest in analysing risk and risk reactions for various research objectives at stake for example sustainability, increased self-sufficiency, income generation for target groups etc.

Let us take the sustainability objective as an example and assume research experts are asked to specify the risky parameter for sustainability in terms of a triangular probability distribution of the potential sustainability effect measured as subjective scores. As with yield increase, the uncertainty of the sustainability distribution would propagate further down via numerical simulation – although calculation procedures may be somewhat different – and would result in a distribution of final total sustainability scores. From this it is straight-forward to incorporate this information into a risk programming model, e.g., an UEP model which would then generate portfolios based on translating sustainability score into utility values. Other objectives could be dealt with in the same fashion, e.g., for the objective "‘income for selected target groups" by defining a probability distribution around the adoption rate or yield increase estimates for selected target groups.

Below, some of the major findings and distinct features of the different modelling approaches are summarised. Some new criteria are added that seem relevant when looking from the operational perspective of a model user who is responsible for operating such risk models. Table 7-5 summarises these findings for UEP, QRP and MOTAD. The first comment regards the required data. Since data are often in short supply and the interrogation of research experts takes up much of the workshop time, data requirement of risk models is an important issue.

The two types of data required in the context of risk modelling are the expectations of the coefficient values – the final returns – and the probability distributions around that expectations. There are two means of acquiring these data. The first is by interrogating workshop participants to obtain estimates of the expected values and variances of the projects' returns, and the second is the description of the probability distributions of uncertain input parameters in conjunction with numerical simulation to generate the distributions of the final returns. Utility efficient models and MOTAD models require numerical simulation because they need the whole sample set while the QRP only requires the expected value and variance of the project returns.

Table 7-5: Advantages and disadvantages of UEP, QRP and MOTAD models

	Maximising expected utility (DEMP or UEP)		Quadratic risk programming (QRP)	Maximisation of total absolute deviation (MOTAD)
Criteria	Non-linear programming	Separable programming		
Objective function	non-linear	linear	quadratic	linear
Data requirement	+	+	+	+
Utility efficiency	++	+	+ -	-
Possible risk preferences				
- Risk averse	yes	yes	yes	yes
- Risk preferring	no	yes	yes	yes
Variation of risk preference	-	--	++	+
Solver availability	+	--	+	-
Solving time	+	++	+	++
Number of constraints	-	++	+	++
Number of activities	--	+	-	+
Model extension	+	+	+	+
Model size	--	-	-	+

++ very good, + good, - poor, -- very poor

Another comment concerns computational convenience, which according to HARDAKER et al. (1997, p. 203) has a much more pronounced impact on model choice than theoretical aspects. The widespread use of MOTAD and E-V models indicate this although UE and DEMP models would seem to be more preferable. Table 7-5 looks at several points related to computational convenience.[18] The most important point is time for generating portfolio solutions. Here, linear models perform much better than non-linear ones. One finding was that solving time is much less affected by an increase in the number of activities and degree of non-linearity than by the numbers of restrictions especially equality restrictions which pose serious limitations to extending non-linear risk models (UEP and QRP) to multiple objectives, incorporating various decision constraints or even of merging risk models with other research allocation models. Therefore, UEP and DEMP models should be seen rather as stand-only applications with the sole focus on risk, rather than as integrated models that embody a much broader spectrum of analytical capability.

7.6 Formulation of an Utility Efficient Programming Model for Multi-Objective Analysis Under Risk

Most programming techniques that can handle multiple objectives under risk are "interactive techniques" which involve a progressive elucidation and definition of the decision makers' preferences by allowing an interaction between him and the model. This way the decision makers transmit their preferences or trade-offs related to various objectives by answering questions raised by the analyst. Pioneers of the interactive modelling techniques are GEOFFRION et al. (1972) who used MOP techniques and DYER (1972) who used goal programming techniques. Several interactive methods have been developed to represent uncertainty of constraint and/or objective function values.

The first method is called "STRANGE" and has been introduced by TEGHEM et al. (1986). STRANGE is an interactive method that is based on eliminating uncertainty through combining the attribute vectors across all states of nature into a single-attribute vector. For example, a two-attribute problem with 3 states of nature will be transformed into a 6 attribute problem under certainty. A second approach by MARESCHAL (1986) is based on simple rank-orders. Each state of nature is solved independently to achieve a rank ordering. The probability of occurrence of the states of nature are then used as weights to acquire a weighted ranking for the determination of the preferred solution.

A third interactive method has been developed by KLEIN et al. (1990). Their approach utilises the concept of multi-attribute utility theory and is based on a two-stage mathematical programming method that is capable of dealing with constraint uncertainty – two-stage constraint utility (TSCU) or objective function uncertainty – two-stage expected

[18] Computational convenience is very much influenced by the solver engine at hand and the different ways of handling the mathematical structure of the model for the different spreadsheet editors. Therefore, all comments made about computational convenience are specific to the Premium solver for MS EXCEL.

utility (TSEU). Interactive techniques for multi-objective decision making are eloquent tools that combine mathematical rigour with a strong focus on interaction and communication between decision makers and the analyst. On the other hand, they require very proficient knowledge in mathematical programming as well as considerable time for conducting the multiple interactive stages with the decision makers.

Less sophistication is required when using UEP programming instead of interactive techniques. An UEP model is easily extendible to cases involving multiple objectives under uncertainty. Based on the stochastic multi-attribute utility function (see formula 5) one can easily construct an UEP model that maximises expected utility of a multi-attribute decision problem. Assuming that the attributes are additive and all other conditions as outlined in section 7-1 hold true the general form of an additive and composite objective function of an UEP model can be expressed as:

(17) maximise $E(U) = \sum_{t=1}^{T} k_t \sum_{k=1}^{n} p_k u_t(\sum_{j=1}^{m} Z_{jkt} X_j)$

in which Z_{jkt} is the return per unit of activity j for observation k and objective t;
X_j is the level of activity j over all observations and objectives with [0; 1] integer values;
m is the number of possible activities;
n is the number of observations;
T is the number of objectives;
$u_t(\sum_{j=1}^{m} Z_{jkt} X_j)$ is the value of the utility function for the portfolio of activities for observation k given u_t is a specific utility function for objective t;
p_k is the probability of the k th state of nature;
$p_k u_t(\sum_{j=1}^{m} Z_{jkt} X_j)$ is the expected utility for the portfolio of activities for objective t and

k_t is a scaling (weighting) factor for objective t taking any value between $0 < k_t < 1$.

When the problem is reduced to certainty, then the maximisation of the expected value E(V) simplifies to the formula:

(18) maximise $E(V) = \sum_{t=1}^{T} k_t v_t(\sum_{j=1}^{m} Z_{jt} X_j)$

in which v_t represents the value function for objective t and
Z_{jt} is the mean return per unit of activity j for objective t and is calculated as the sample mean from the n observations.

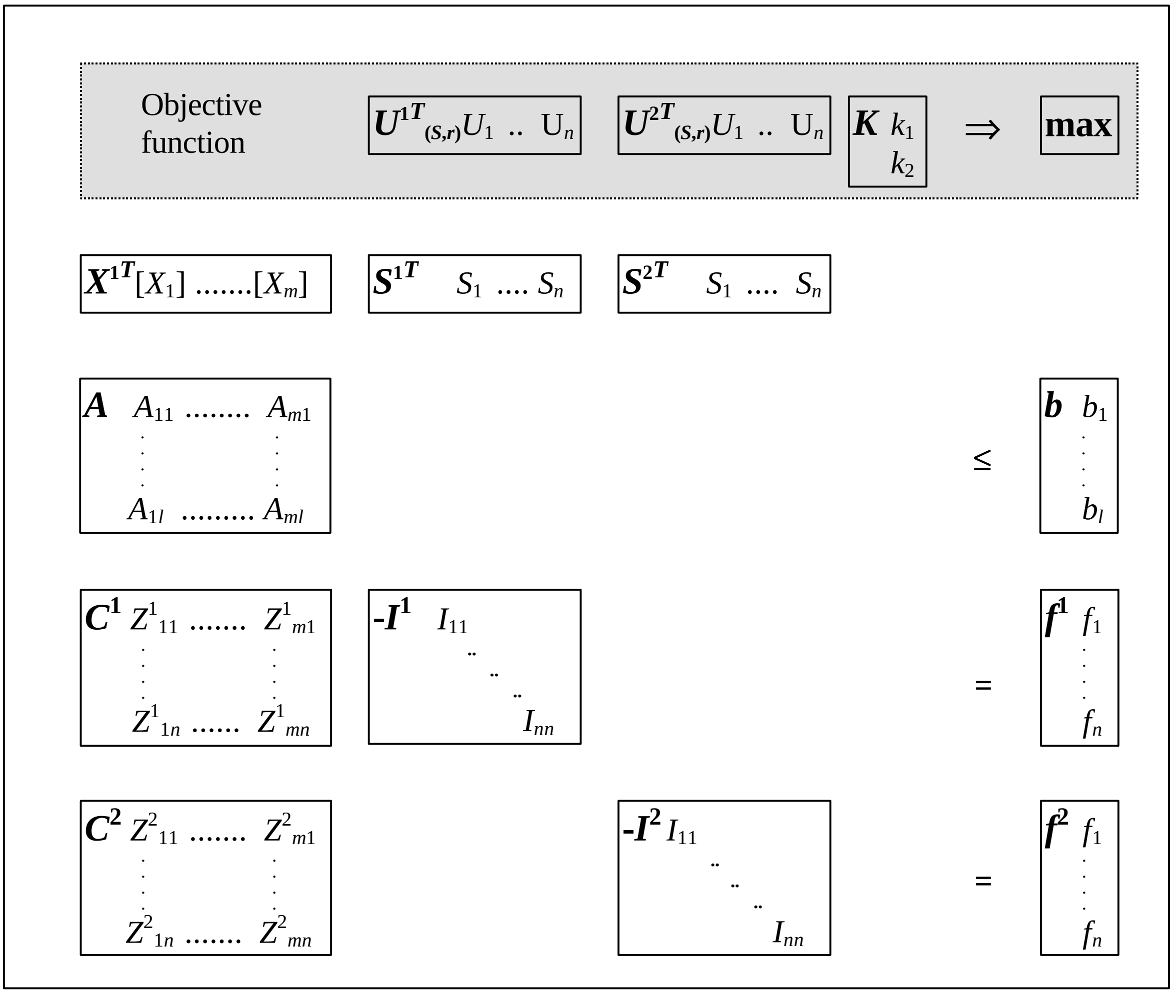
In principle, one may approach the optimisation problem under uncertainty by first measuring a decision maker's multi-attribute utility function and preference weights explicitly and then solving using a mathematical programming algorithm. Such an approach usually suffers from numerous measurement complexities due to utility function and preference weight elicitation. The measurement task becomes less complex when applying an UEP model and when a sensitivity analysis is carried out over the whole range of possible preference weights. In the same way that the UEP structure was formulated for a single-objective problem, the UEP formulation here replaces the multi-objective utility function by the multi-objective Pratt-Arrow coefficient $r_a(x)$, thus avoiding the specification of the exact functional form of the t utility functions, and sensitivity analysis of preference weight substitutes for the elicitation of the exact objective weights. Both steps can help to keep required information to a minimum.

As a point of departure for the subsequent analyses this section starts with the development of the mathematical programming tableau for the UEP model. For ease of exposition, only two objectives are considered. Also, the following assumptions are made: utility and preference independence, a quasi-separable multi-attribute utility function of the negative exponential functional type ("expo-power" function), CARA property for all utility functions, and an additive value function of the two objectives. If these assumptions hold true the structure of a multi-objective UEP model can be developed such as outlined in Figure 7-9.

The UEP tableau described here has basically the same structure as the single objective UEP tableau outlined in section 7.3.1. Thus, model elements and notation are very similar. Here, the C^1 and C^2 matrices represent the 200 states of nature of the objective function coefficients for objective 1 and 2. The matrices I^1 and I^2 aggregate each state of nature across all projects. Objective function values $S_{i,\ \dots,n}$ are then translated into utility values $U_{i,\dots,n}$ through the specification of the multi-objective utility function. A new vector K is added which multiplies the sum or the mean of the utility values with the preference weights k_1 and k_2.

The objective function which is subject to maximisation then becomes the sum of the expected utility values for each objective, weighted by the preference weights. With this UEP model it is possible to explore the trade-off between two objectives for any given risk aversion level by changing preference weights and, furthermore, to examine the effects of different attitudes towards risk on the trade-offs between the two objectives by changing the values of $r_a(x)$. In fact, the UEP model as outlined herein carries the possibility of a three-dimensional trade-off analysis including the two objectives plus risk.

Figure 7-9: Outline of an utility efficient programming tableau for a two-objective programming model



$X_1, ..., X_m$ are [0; 1] decision variables representing research projects;

$A_{11}, ..., A_{ml}$ are technical coefficients for resource use, etc.;

$Z^1_{11}, ..., Z^1_{mn}$ and $Z^2_{11}, ..., Z^2_{mn}$ denote coefficients of the projects' contribution to objective 1 and objective 2 including n observations for each project;

$I^1_{11}, ..., I^1_{nn}$ and $I^2_{11}, ..., I^2_{nn}$ are diagonal elements to calculate the contributions of a portfolio to objective 1 and objective 2 for each state of nature;

$S^1_1, ..., S^1_n$ and $S^2_1, ..., S^2_n$ are summation variables representing the contributions of a research portfolio to objective 1 and objective 2 for each state of nature;

$U^1_1, ..., U^1_n$ and $U^2_1, ..., U^2_n$ are summation variables representing the utility of a research portfolio to objective 1 and objective 2 for each state of nature;

$b_1, ..., b_l$ are right-hand side coefficients representing resource availability and other constraints;

$f^1_1, ...f^1_n$ and $f^2_1, ...f^2_n$ represent initial contribution to objective 1 and objective 2 for each state of nature.

7.7 Application of the Utility Efficient Programming Model to Analysing the Trade-Offs Between Efficiency and Equity Objective under Risk

Based on the general structure of the UEP tableau outlined in the preceding section an UEP model has been developed and applied to the case study to investigate decision options for research planning when multiple and conflicting objectives are involved, research outcomes are stochastic, and decision makers may exhibit different preferences towards risk. The central focus is on the trade-offs between maximising the economic gains from research given limited research resources (efficiency objective) and achieving desired distributional effects of the gains from research for different societal groups and regions (equity objective). For the analyses ahead the equity objective is looked at from two different angles: one is the distinction between consumers and producers of milk, and the second is the spatial distribution of the economic gains across different regions in Kenya. Before moving to the results of the analyses, some general remarks are made with respect to the definition of equity and how equity can be specified in an economic surplus framework.

7.7.1 The Notion of Equity in an Economic Surplus Framework

Equity objective is geared to improving the well-being of particular groups within the society, such as poor, producers and consumers, women, ethnic groups, regions etc. The pursuit of equity objective is often at odds with the pursuit of purely growth objectives. Historically, technological innovation and productivity gains have occurred in areas enjoying favourable topographic and agronomic conditions, e.g., in well-watered or irrigated areas for high yielding varieties of the "Green revolution" (LIPTON and LONGHURST, 1990). In contrast, more marginal production environments have lagged in terms of productivity gains exacerbating inter-regional productivity differences and income inequalities. This has partly been the result of the inherent difficulties of developing technologies suited to the more difficult marginal environments. In many cases, it is also presumable the result of institutional strategies for maximising the potential payoff to research activities (RENKOW, 1993).

It seems that progress on the definition and impact assessment for equity in agricultural research has been more limited than for the efficiency objective. Defining meaningful concepts for equity and integrating them into ex-ante research evaluation and priority setting is more cumbersome than it is for the efficiency objective. Different concepts and different ways of evaluating equity may lead to contradictory predictions of the distributional consequences of research and also to various research strategies. To make the notion of equity tractable in an economic surplus framework not every equity concept is suitable. The choice for defining equity is rather limited. The pursuit of equity in an economic surplus methods mainly focuses on the distribution of benefits arising from research which can be delineated into only few directions, either by:

- regions, countries and other spatial dimensions;
- economic groups in the society such as consumers and producers; or
- adopting and non-adopting regions, social groups, farm households of the new technologies generated from research.

While equity is often a social-political issue, it would be wrong to suppose that non of these directions would have an strong appeal on equity. The differentiation of research benefit by regions may be justified since there is often, but by no means, always a significant relationship between the pattern of income distribution and agro-ecological factors, usually based on the correlation between land quality and farm income. In such circumstances, differentiating research benefit by spatial aspects can be a useful means for approximating the distributional consequences of agricultural research for disadvantaged social groups. A second possibility is the partition of the benefits by consumers and producers.[19] The general message of the welfare effects of supply shift analysed by partial equilibrium models is that in open economies producers reap the lion's share of the research benefits whereas in closed economies it is the consumers who benefit most via price effects in output markets if demand is relatively inelastic.

Similarly to the spatial distribution, equity expressed as the gains from research to consumers versus producers may have a poverty focus as well, but probably less pronounced. Whenever gains are mostly captured by consumers the impact of research on income distribution is progressive. Poor people usually spend a large proportion of their budget on food and the proportional gains on their real income is larger than that of rich people who spent proportionally less on food (BINSWANGER and RYAN, 1977). On the production side the coincidence with the poverty issue is less striking since empirical evidence of the distributional effects on farm level shows much controversy depending on the commodity, the characteristics of new technologies and countries in which technical progress has taken place.

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[19] Much work has been done on analysing the distributional consequences of research and technical change using partial equilibrium or general equilibrium models, e.g., AYER and SCHUH (1972); AKINO and HAYAMI (1975), and HAYAMI and HERDT (1977).

A third alternative to defining equity is to subdivide agricultural producers according to technology adoption. Whether technology adoption is related to income and poverty cannot be decided a priori but must be judged differently. Much convincing evidence has supported a strong coincidence between technology uptake and income situation (small or large farmers). However, technology adoption is much more difficult to integrate into an economic surplus framework than the spatial or consumer-producer concepts. The first problem is lack of information concerning the identification of the groups of adopting and non-adopting agricultural households, and to assess their production and consumption status. The second problem is the treatment of these groups as separate entities (market segments) in a trade model including the specification of demand and supply functions. Therefore, the notion of equity in terms of adoption behaviour has not gained widespread application in the context of priority setting.

7.7.2 Trade-off Analysis between Efficiency and Equity with Equity Expressed as Benefit Distribution by Agro-ecological Zones

Presumably the most intuitive interpretation of distributional or equity aspects for our case study is the distinction of research benefits by agro-ecological zone. This spatial perspective may constitute, for many occasions, a good approximation for other criteria used as distributional indicators such as farming systems, farm size, income levels, etc., since all these criteria may have strong overlap with the production sites and regions. As a first step, the equity focus of dairy research is defined on a regional basis by subdivision of all AEZs into two regional groups, each representing one objective. Impact information is sorted and aggregated over these groups. The main criteria chosen for the grouping of the regions are population density and, closely linked to that, available arable land per head. So, the first group is made up of the high rainfall 1 (HR 1), high-rainfall 2 (HR 2) and medium-rainfall 2 (MR 2) zones with a land man ratio below zonal average as indicated in Table 7-6. The second group takes up all other zones, namely, MR 1, MR 3 and LR 1; all of them located in the drier parts of the country and covering larger areas of land.

The first group is not only the group where the majority of production and consumption of milk takes place but is also characterised by the most urgent need to adjust the mode of production. Low land-man ratio means that more land saving and labour intensive technologies are required in order to feed an increasing number of rural households on the same land. Thus, the introduction of improved dairy technologies such as zero-grazing systems in these regions may be given high priority. For the other regional group, dairy research may not be the key researchable commodity. In the light of this, group 1 may be labelled as the "core" dairy group while group 2 as the "marginal" dairy group.

Table 7-6: Area, population and land-man ratio by agro-ecological zone

Agro-ecological zones (AEZ)	Total area (sq. km)	Population	Land-man ratio* (sq. km per head)
High-rainfall 1 (HR 1)	7,036.08	1,569,006	0.4484
High-rainfall 2 (HR 2)	25,582.94	6,581,772	0.3887
Medium-rainfall 1 (MR 1)	19,842.98	2,375,162	0.8354
Medium-rainfall 2 (MR 2)	34,902.66	4,762,955	0.7328
Medium-rainfall 3 (MR 3)	11,387.34	617,197	1.8450
Low-rainfall 1 (LR 1)	63,201.28	4,066,788	1.5540
Grouping of agro-ecological zones			
→	**"Core" dairy group**		
→	**"Marginal" dairy group**		

* A more accurate indicator of land scarcity than total area per capita would be the ratio of arable land to population size, corrected for land productivity differences. But this information is not available.

Source: Data from the GIS system employed in the priority setting workshop 1996.

Table 7-7 shows how the economic gains from the 19 dairy projects would be allocated to the two groups. It can be seen that the pattern looks different. Depending on the region-specific adoption and yield increase parameters, research impact could be totally absorbed by the "core" regions (e.g., RP 5) or could be directed mainly to "marginal" regions (e.g., RP 1). However, apart from the extreme examples, the large part of the gains for most projects would be captured by the "core" dairy group. The trade-off analysis was executed by applying the "weighting" method of multi-objective programming. The objective function of the UEP model to be maximised is composed of the two objectives defined as the total economic surplus for group 1 and group 2 and represented by the 200 net present value estimates from simulation.[20] Preference weights w_i between 0 and 1 are attached to the economic gains accruing to each group. Technically, w_i constitute multipliers for the net

[20] Subject to maximisation are only the 6 productive regions of the two groups. Consumer surplus for the urban markets and Nairobi are excluded. Therefore, solutions are likely to differ from those that would result from maximisation of the total surplus given the same budget level.

present values in each group. With parametric variation of the preference weights w_1 and w_2 between 0 and 1 such that w_1 and w_2 sum up to 1, different trade-off curves from alternative research portfolios were generated over the 4 risk aversion levels: $r_a(x)$ = 0.00005, 0.0001 and 0.0005 including risk neutrality at $r_a(x)$ = 0. If w_1 is zero and w_2 is 1, the UEP model generates a research portfolio that maximises the economic gains for the second objective, i.e., for the "marginal" dairy group, while opposite preference weights establish the maximisation of the first objective. The risk aversion values $r_a(x)$ were chosen in order to screen the largest possible risk interval (the UEP model reaches its reliability frontier at around $r_a(x)$ = 0.0005). Furthermore, the values of $r_a(x)$ were assumed equal across the two objectives for every parametric variation. Budget limit was set at 40 million KSh allowing approximately two-third of the dairy projects being implemented.

Table 7-7: Distribution of the economic gains by project type and the "core" and "marginal" dairy groups (net present value in KSh million)

Research project type	Group 1: "core" dairy group		Group 2: "marginal" dairy group		Ratio of mean net present value between group 1 and group 2
	Mean net present value (KSh million)	Standard deviation.	Mean net present value (KSh million)	Standard deviation.	Group 1/group 2
RP 1	35.58	9.14	95.45	26.95	0.37
RP 2	183.42	65.54	154.21	55.57	1.19
RP 3	10,902.25	1,728.35	554.85	92.73	19.65
RP 4	9,745.95	2,141.33	1,698.03	405.74	5.74
RP 5	126.94	6.91	0.00	0.00	/
RP 6	5,595.16	1,062.61	1,390.01	291.85	4.03
RP 7	9,611.52	1,900.82	2,565.87	579.43	3.75
RP 8	2,396.75	300.20	543.35	127.35	4.41
RP 9	4,433.72	894.36	47.79	53.37	92.77
RP 10	678.01	74.72	351.29	43.98	1.93
RP 11	3,788.13	543.19	2,409.16	372.50	1.57
RP 12	1,481.86	201.72	791.32	136.59	1.87
RP 13	574.21	118.88	293.36	71.10	1.96
RP 14	1,747.43	605.70	454.81	222.19	3.84
RP 15	4,442.24	991.54	2,966.80	632.85	1.5
RP 16	2,062.43	400.94	1,276.12	164.82	1.62
RP 17	17.45	3.23	568.76	122.17	0.03
RP 18	2,964.70	394.29	1,774.89	260.85	1.67
RP 19	4,011.74	648.89	2,437.04	407.54	1.65

Table 7-8 highlights selected results from the trade-off analysis with the exposition of alternative research portfolios for varying weights between the two objectives. As could be foreseen from the heterogeneous regional impact structure of the research projects, variability in the generated portfolios is considerable when the importance of the objectives is changed. Increasing preference weights on the "marginal" dairy group does not only reduce the NPV for the "core" group but also leads to the decline in total surplus across all productive AEZs.

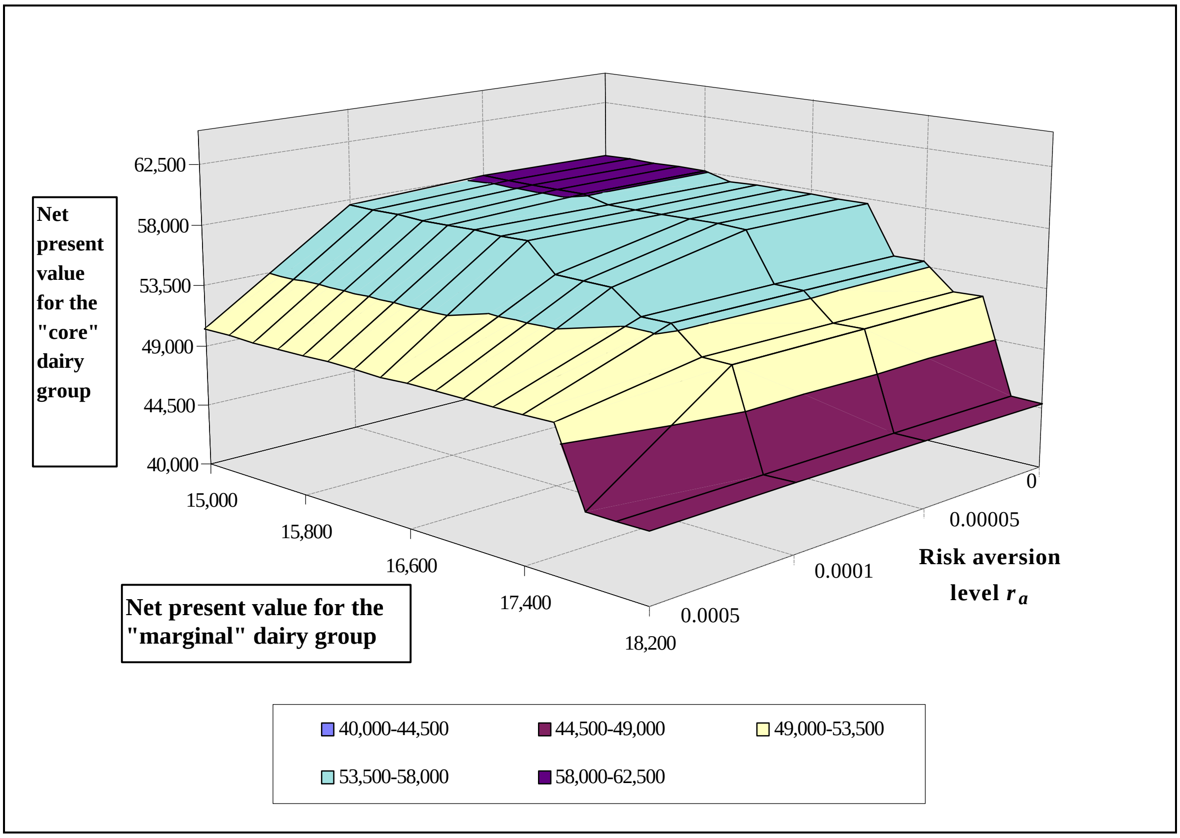
Table 7-8: Trade-off results between the "core" and the "marginal" dairy group assuming risk neutrality ($r_a(x)$ = 0; budget available: 40 million KSh)

Weights on objective 1	**Research project type**																			Economic gains expressed as mean net present value (KSh million)		
"Core" dairy group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	"Core" dairy group	"Marginal" dairy group	Total
1			■	■	■	■	■	■	■	■	■	■	■	■				■	■	58,058	15,312	73,370
0.9			■	■	■	■	■	■	■	■	■	■	■	■				■	■	58,058	15,312	73,370
0.8			■	■	■	■	■	■	■	■	■	■	■	■				■	■	58,058	15,312	73,370
0.7			■	■	■	■	■	■	■	■	■	■	■	■				■	■	58,058	15,312	73,370
0.6			■	■		■	■		■	■	■	■	■	■		■		■	■	57,597	16,045	73,642
0.5			■	■		■	■		■	■	■	■	■	■		■		■	■	57,597	16,045	73,642
0.4			■	■		■	■		■	■	■	■	■	■		■		■	■	57,597	16,045	73,642
0.3			■	■		■	■		■	■	■	■	■	■		■		■	■	57,597	16,045	73,642
0.2			■	■	■	■	■			■	■	■	■		■			■	■	53,923	17,233	71,155
0.1			■	■			■			■	■	■	■	■	■	■		■	■	52,010	17,574	69,584
0				■		■	■			■	■	■	■		■	■		■	■	44,956	17,954	62,910

The shaded boxes indicate the proposed research projects; NPV in KSh million.

This implies that dairy research targeted at the regions in the "marginal" group would cause considerable efficiency losses in overall NPV which would decline by around 15 per cent from 73,370 to around 62,910 million KSh. Figure 7-10 highlights the complete results including all other risk aversion levels, and visualises them in compact form as a three-dimensional surface plot. The plot embodies two different trade-off types: the first type is the economic trade-off between the two regional groups, and the second type addresses the relationship between the degree of risk aversion and possible achievable NPV (efficiency gains versus risk reduction). With respect to the first type, significant trade-offs exist between maximising NPV for each of the two groups.

Figure 7-10: Trade-off results between the "core" and the "marginal" dairy group for different risk aversion levels (budget available: 40 million KSh)

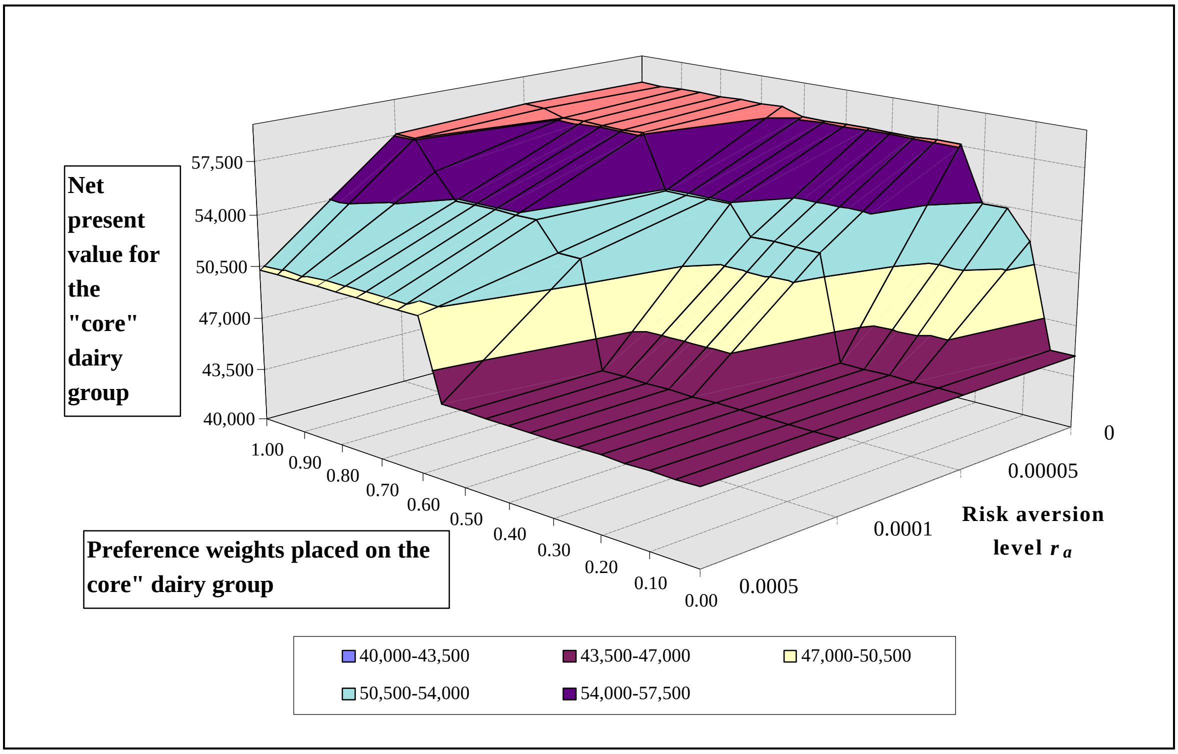


Under risk neutrality condition, placing increasing weights on the "marginal" group while reducing the weights on the "core" dairy group would imply a drop in NPV for the "core" group of 22,5 per cent from an initial 58,000 to around 45,000 million KSh. For the opposite direction, NPV for group 2 would be reduced by around 15 per cent from an initial value of 18,000 to a final value of 15,300 million KSh. With increasing risk aversion, the number of alternative solutions and the absolute size of the losses in NPV for each group decreases. For example, at r_a (x) = 0.0005, the costs in terms of foregone NPV in the competing group for placing stronger emphasis on the "core" group reaches around 10 per cent and for the "marginal" group 5.5 per cent respectively. One possible reason for the decreasing strength of the trade-offs can be seen in the efficiency losses due to increasing risk aversion. A risk neutral portfolio has, in general, higher expected returns but greater variability than a risk averse portfolio which, in turn, reduces the potential range in which the NPV for the two groups can vary.

Another observation from Figure 7-10 is that the number of alternative portfolios declines with increasing risk aversion, e.g., the trade-off curve at r_a (x) = 0.0005 is made up of only two portfolios. This result may correctly reflect the real situation, but also may be due to technical problems during optimisation. With increasing concavity of the utility function (with increasing risk aversion) the differences in the expected utilities of alternative portfolios may become too small for non-linear MP solver to detect all possible portfolios.

Figure 7-10 does not indicate the exact preference weights attached to each alternative portfolio. Figure 7-11 is a modified version of the three-dimensional surface plot in Figure 7-10 and indicates for the same set of alternative research portfolios the exact preference weights placed on both dairy groups. This type of presentation is better suited for inspection of the trade-offs between the economic gains allocated to the two groups.

Figure 7-11: The effect of risk aversion and preference weights on the economic gains for the "core" dairy group (budget available: 40 million KSh)



Because of dimensionality problems, Figure 7-11 highlights only the economic gains for the "core" dairy group in addition to the preference weights for the "core dairy group and different risk aversion levels. Inspection of Figure 7-11 reveal that variation in the portfolio solutions is evenly spread across the whole range of the preference weights on the "core" dairy group. However, with increasing risk aversion alternative research portfolios are more plentiful in the upper half of the preference weight (between $1 \leq w_1 \leq 0.5$).

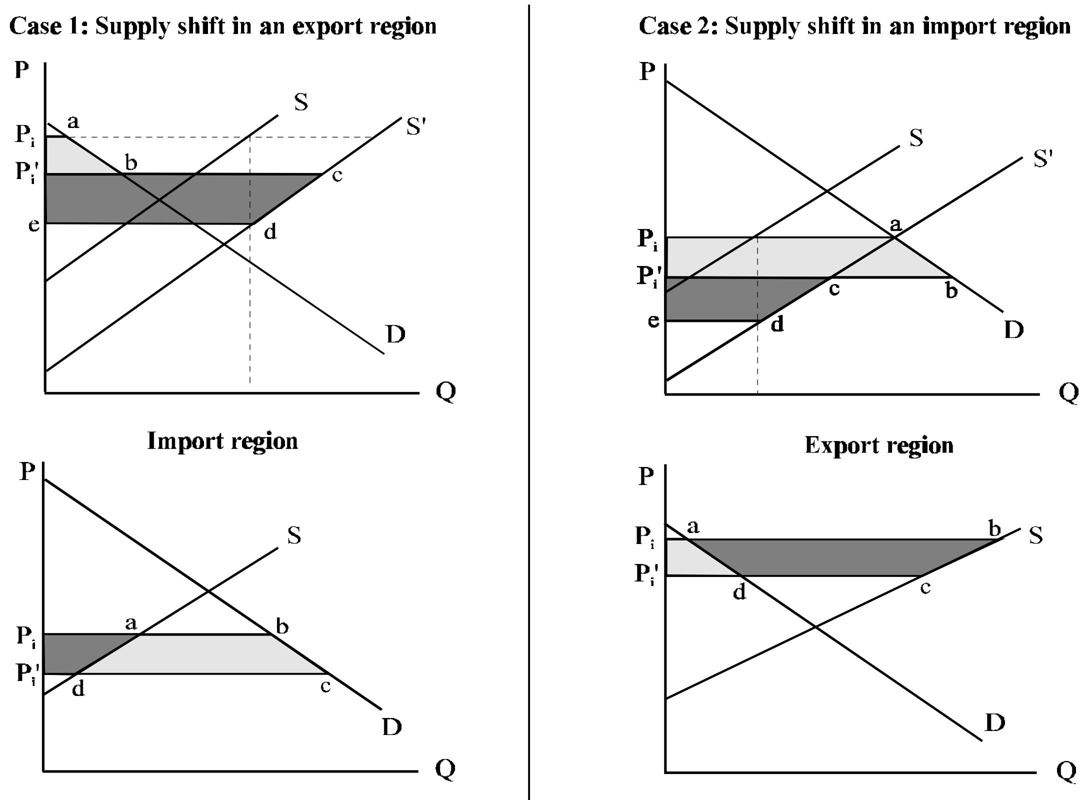
7.7.3 Trade-Off Analysis between Efficiency and Equity with Equity Expressed as Benefit Distribution by Producers and Consumers

This section proceeds with analysing equity concern from another angle and looks at the production and consumption aspects of the Kenyan dairy sector. For the analysis ahead equity is understood as the targeting of Kenyan producers or consumers of milk as beneficiaries of the economic gains from research. With the distinction of consumers versus producers it is possible to directly address one of the fundamental policy trade-offs between increasing farmers' income through new and more efficient production technologies on the one hand and providing consumers, especially urban and rural poor, with sufficient quantities of food at reasonable prices on the other hand. If the research program would have been given both policy mandates, running a bi-objective research allocation model built on maximising either the economic gains to producers or consumers could be a fairly good representation for the study of the trade-offs between these two policy objectives.

As was mentioned during the discussion on the economic surplus concept in chapter 2, distinguishing research benefits by consumer and producer groups has a strong overlap with the distinction of the main production surplus regions and the deficit regions, i.e., the urban centres and the capital Nairobi. If strong emphasis in placed on allocating the gains from dairy research to the Kenyan dairy producers, the resultant research portfolios tend to favour those research projects that induce large shifts in the supply schedule in production surplus regions. On the other hand it discriminates against research projects that causes large supply shifts in deficit regions and small or no shifts in surplus regions.

This fact can be recapitulated from Figure 7-12 which shows the economic gains for consumers and producers from research taking place in an exporting (surplus) and an importing (deficit) region. The effects of research in a surplus region (indicated by the shift of the supply curve from S to S' and a reduction of the price level from P_i to P_i') are large gains for producers in the surplus region (area $P_i'cde$) and relatively low losses in the deficit region (area P_iadP_i'). If, on the other hand, research predominately takes place in deficit regions the overall gains to producers are much smaller or can even be negative. This is because gains to producers are relatively small in the deficit region (area $P_i'cde$) while the losses in the surplus region are significant (area P_ibcd). On aggregate, the proportionate gains to producers – compared to those allocated to consumers – are much higher if research has its greatest impact in the production surplus regions, while the opposite is true if research predominately affects the deficit regions.

Figure 7-12: Distribution of the research gains between producers and consumers for a traded good in a two-region market model



Case 1: Export region:

Δ PS = area + ($P_i'cde$)

Δ CS = area + (P_iabP_i')

Δ TS = area + (P_iabcde)

Import region:

Δ PS = area - (P_iadP_i')

Δ CS = area + (P_ibcP_i')

Δ TS = area + ($abcd$)

Case 2: Import region

Δ PS = area + ($P_i'cde$)

Δ CS = area + (P_iabP_i')

Δ TS = area + (P_iabcde)

Export region

Δ PS = area - (P_ibcd)

Δ CS = area + (P_iadP_i')

Δ TS = area - ($abcd$)

Δ PS = changes in producer surplus, Δ CS = changes in consumer surplus, and Δ TS = changes in total surplus.

Source: Modified, after ALSTON et al. (1995, p. 215; 218).

For the following analysis, not only the production regions but also all other markets including the coastal urban areas and Nairobi are considered. The specific conditions of the Kenyan dairy market suggest that the consumer surplus aspect has strong poverty and urban implication. The urban implication is due to the dynamic growth of milk consumption in urban households and the poverty implication to the important role that milk plays in the diet of the urban poor. Table 7-9 below depicts the proportion of potential consumer and producer surplus gains from the 19 different dairy research projects. Projects with the highest share captured by producers are those from the "feed resources and utilisation thrust", namely projects 3, 4, 7 and 11, which occupy the top ranks in terms of NPV and CBR. They do not show only the best overall adoption rates and yield increase levels but have in common an exceptionally good performance in the large dairy surplus regions HR 1, MR 1 and MR 2 in which reduction in production costs induce large welfare gains. In sharp contrast to this are projects whose impacts are mainly captured by consumers. The majority of these projects belong to the "animal health and hygiene" thrust, e.g., project types 10, 12 and 13, and the "breeding and genetic improvement" thrust, e.g., project 17. These projects have fairly equal adoption rates and yield increases across all AEZs and have, on average, lower NPV and CBR.

Table 7-9: Research Gains allocated to consumers and producers by research project type (in KSh million)

	Mean present value	Mean net present value	Mean producer surplus	Mean consumer surplus	Ratio of producer/ consumer surplus
RP 1	133.03	127.56	131.03	2.00	65.50
RP 2	400.22	395.86	-348.09	748.31	-0.47
RP 3	12025.53	12,022.28	5,211.10	6,814.43	0.77
RP 4	12025.85	12,021.78	5,055.79	6,970.06	0.73
RP 5	129.94	125.44	126.94	3.00	42.33
RP 6	7346.89	7,340.22	3,010.38	4,336.51	0.69
RP 7	12794.01	12,790.13	5,403.37	7,390.64	0.73
RP 8	3190.21	3,186.38	194.67	2,995.54	0.07
RP 9	4750.36	4,745.87	1,527.60	3,222.76	0.47
RP 10	1149.83	1,149.29	-292.98	1,442.81	-0.20
RP 11	6498.91	6,498.20	2,881.72	3,617.19	0.80
RP 12	2511.5	2,511.19	-341.32	2,852.82	-0.12
RP 13	974.17	973.73	-301.07	1,275.24	-0.24
RP 14	2406.94	2,403.58	-47.44	2,454.38	-0.02
RP 15	7507.38	7,496.12	2,722.75	4,784.63	0.57
RP 16	2835.5	2,829.69	468.12	2,367.38	0.20
RP 17	685.11	679.30	-498.10	1,183.21	-0.42
RP 18	5010.25	5,007.16	1,765.62	3,244.63	0.54
RP 19	6777.63	6,774.55	2,838.65	3,938.98	0.72

The present value is the sum of the consumer and producer surplus; the net present value is the present value mine discounted research costs.

Table 7-9 suggests a very heterogeneous picture of how the gains are distributed among producers and consumers. This becomes especially clear from the ratio of the gains to producers and consumers. Ratios greater 1 indicate that the largest share is captured by producers, below 1 consumers gain most, and a negative ratio indicates losses in producer surplus. The general tendency is obvious: the gains to consumers outweigh gains to producers which can be traced back to the rather inelastic demand and supply functions used in the regional trade model. However, the producer-consumer ratio significantly differs in absolute terms. In light of these differences it can be easily foreseen that research portfolios will not be unaffected by preference changes attached to the producers and consumers.

Table 7-10 summarises selected results from the trade-off analysis. Portfolios were generated using the “weighting“ method with changing weights on maximising producer and consumer surplus. Available budget level was fixed at 40 million KSh and the risk aversion interval was defined between $r_a(x) = 0$ and 0.001.

Table 7-10: Selected trade-off results between producer and consumer surplus assuming risk neutrality ($r_a(x) = 0$; budget available: 40 million KSh)

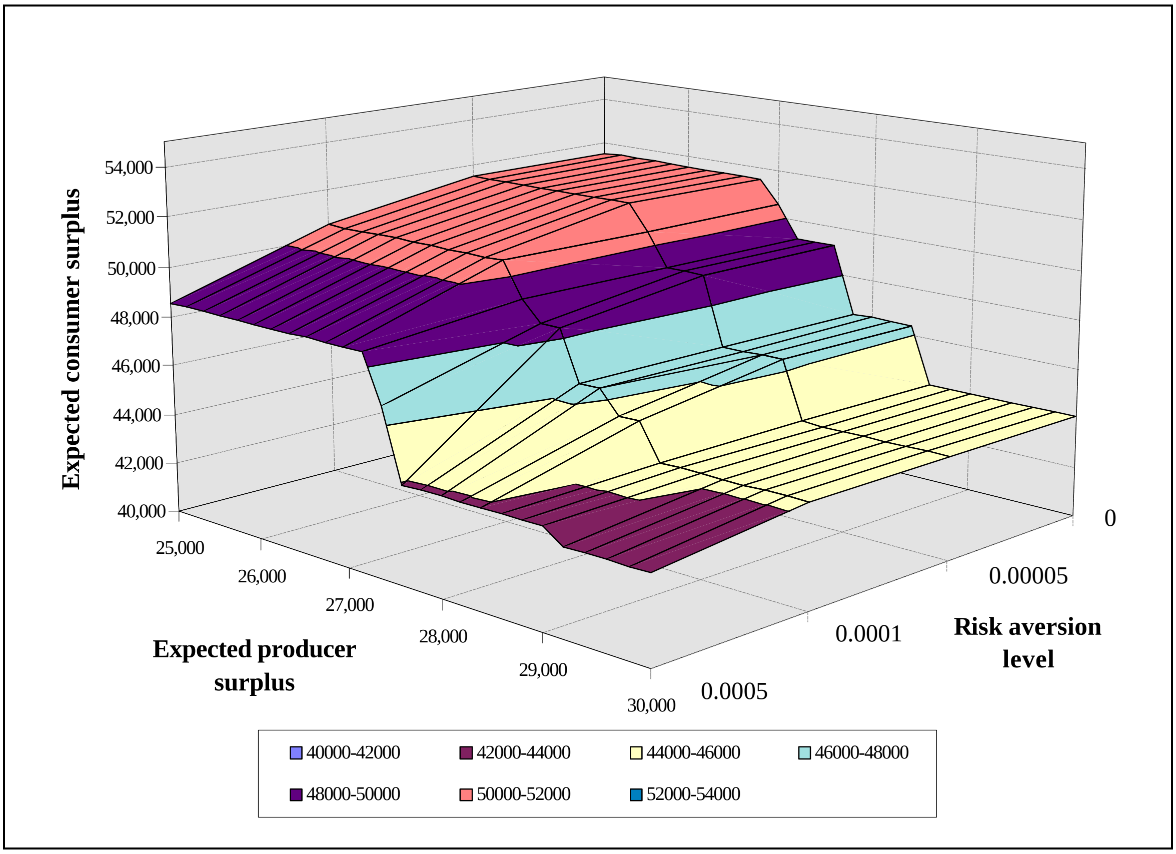
Preference weights on maximising producer surplus	**Research project type**																			Producer surplus	Consumer surplus	Total surplus
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	in KSh million		
1.00			■	■	■	■	■				■				■			■	■	29,084	44,093	73,177
0.90			■	■	■	■	■				■				■			■	■	29,084	44,093	73,177
0.80			■	■		■	■				■	■		■	■			■	■	28,501	46,404	74,905
0.70			■	■		■	■	■	■	■	■	■				■		■	■	27,723	49,194	76,917
0.60			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589
0.50			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589
0.40			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589
0.30			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589
0.20			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589
0.10			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589
0.00			■	■	■	■	■	■	■	■	■	■	■	■				■	■	27,033	50,556	77,589

The shaded boxes indicate the proposed research projects

Placing full weight to producer surplus generates a research portfolio composed of projects mainly from the "feed resources and utilisation" thrust including the top ranking projects with regard to net present value and cost-benefit ratio and with the highest share of producer surplus. As soon as higher weights are placed on consumer surplus, projects with a high proportion of producer surplus (e.g., RP 15) are successively replaced by projects that favour consumers. The composition of the research portfolio then remains unchanged for preference weights on producer surplus between 0.6 and 0.0. Examining the strength of conflict between consumers and producers, the opportunity costs for the pursuit of maximising dairy farmers' income would be around a 13 per cent loss in consumer surplus. On the other hand dairy research policy that is fully targeted at the Kenyan consumers would reduce producer surplus by a maximum amount of around 7 per cent. On purely efficiency grounds (total NPV) a consumer orientated strategy would perform slightly better than a strategy that is solely focused on the well-being of producers.

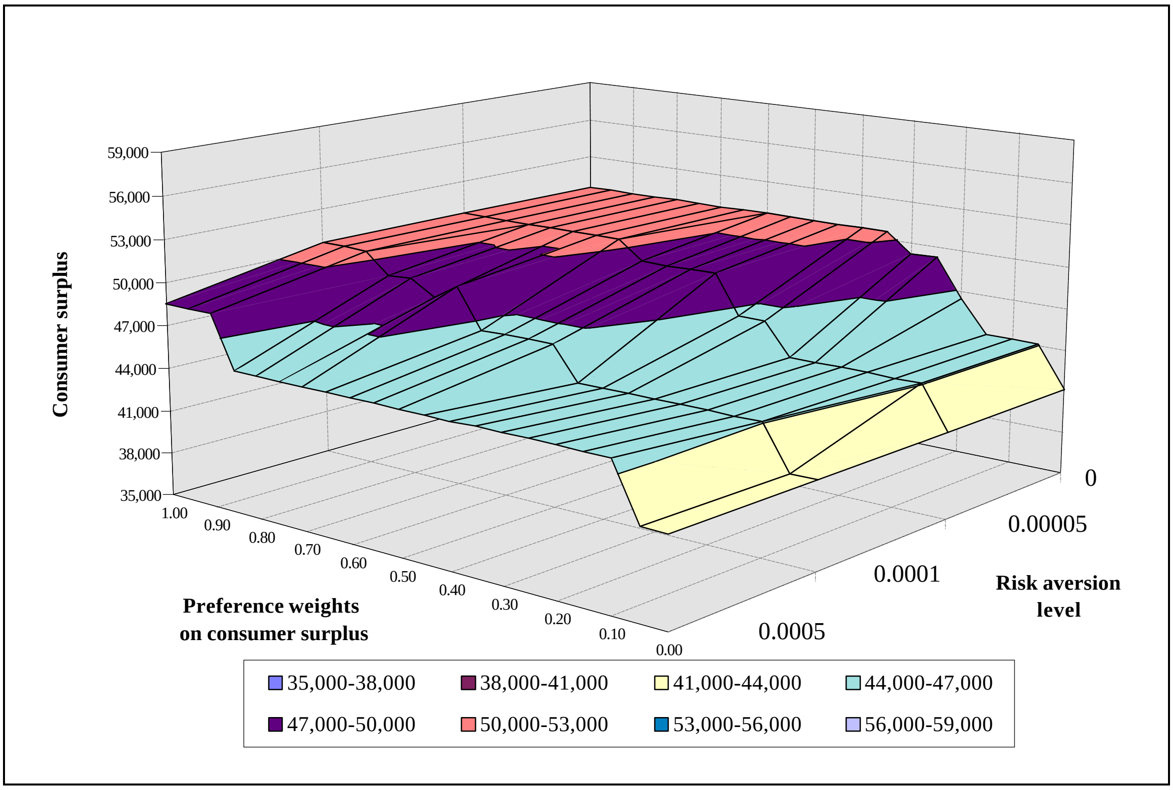
Figure 7-13 and Figure 7-14 present the complete results from the trade-off analysis between producer and consumer surplus including three more risk aversion levels. A general finding is that portfolio variability can be observed with different sets of preference weights on consumer and producer groups as well as with changing preferences towards risk.

Figure 7-13: Trade-off results between producer and consumer surplus for different risk aversion levels (budget limit: 40 million KSh)



The way trade-off curves alter for different preferences towards risk parallels many of the findings from the trade-off analysis between the "core" and "marginal" dairy group. Moving from risk neutrality to strong risk aversion, the efficiency frontiers narrow down, but somewhat less significantly than in Figure 7-13 and Figure 7-14. So, the suggestion that decision makers have to consider a variety of alternative choice becomes somewhat less evident. Information from Figure 7-14 which is based on constant preference weights reveal that, assuming decision makers would value consumer and producer surplus similarly, then the choice of an optimal research portfolio is rather clear-cut. This holds true for any risk aversion level under examination. Based on these findings, policy makers would be well advised not be too much concerned with the different interest of consumers and producers if this discussion is on the agenda. On the other hand, analysts would need to give a rather different advise to decision makers concerning the inherent conflict between the "core" and the "marginal" dairy groups.

Figure 7-14: The effect of risk aversion on the trade-offs between producer and consumer surplus (budget limit: 40 million KSh)



So far, the policy model for allocating research resources and developing research strategies has been extended to a multi-objective and stochastic framework. As an example, two sets of equity objectives, defined differently, were applied to the national dairy research program to show how mathematical programming models can operate under this framework and give useful insights into the simultaneous effects of risk and multiple objectives. The outlined study is, by far, not complete. Every other possible combination of multiple objectives, if meaningful, could be thought of and analysed in the same fashion. The motivation for taking equity objective was simply that trade-offs between defined regions and between producers and consumers turned out very clearly, so that the concept behind multi-objective analysis could be visualised. Multi-objective programming under uncertainty has not attracted much attention. The majority of published policy models treat multiple objectives and risk in isolation. Besides interactive programming techniques, it was shown that the effort required to enhance mathematical programming in this way is justifiable compared to the interesting insights that can be gained from such trade-off analyses.

8 Conclusions and Implications for Economic Modelling in Priority Setting for Agricultural Research

The central focus of this study has been on methodological issues in program-level priority setting for agricultural research. Two major steps in the priority setting process have been given special attention, namely the ex-ante assessment of research alternatives and the development of research plans where economic modelling plays a vital role. The overall aim of the study was to contribute to methodological improvements in research evaluation and decision making. The ignorance of risk and uncertainty and deficits in the treatment of complexity, which are a common hurdles in research program planning, were the main motivation for testing a set of economic modelling techniques which are rarely seen in priority setting so far.

Applying these techniques to a concrete priority setting example in Kenya has given prove to the practicality of these methods and easy integration into standard priority setting procedures. In response to the predominantly methodological focus and the effort spent on the model descriptions, this study did not attempt to provide a comprehensive and detailed overview of the model results from the case study but is kept rather short.

However, a general finding from the case study is that empirical evidence has been added to the hypothesis that risk and decision complexity need a sound and formal recognition in the context of research planning. It came out very clearly that research planners are faced with considerable ambiguity when decisions are to be made on the type of research activities and the future direction of a complete research program as soon as the research program's mandate involves multiple objectives. Mathematical programming models have shown to be useful decision aids by providing planners with a broad range of decision options where the implications of multiple objectives and various other planning aspects can be studied very well.

Similar conclusions can be drawn from the study of risk and uncertainty which have been analysed by stochastic dominance and stochastic mathematical programming. Uncertainty has a major bearing on the quality of decisions by providing research managers with information on the riskiness of research projects, the reliability of evaluation results, and the consequences of different attitudes towards risk.

All these findings are surprising to some degree. Compared to other priority setting exercises documented in the literature the Kenyan example can be described as a rather small exercise due to its limited number of research projects. Also the number of research objectives has finally been reduced to the efficiency and equity objectives only, with both related to the economic dimension of research. It is reasonable to assume that the analytical scope and insights into decision complexity and riskiness would be even more plentiful if the enhanced methods could be employed in large-scale priority setting exercises.

However, due to the large variety of priority setting efforts these methods may not be equally suitable. Specific conditions are required such that the use of these methods can justify the costs. Most promising are priority setting exercises for commodity research where research impact is derived from a market framework or cost-benefit analysis, and evaluation results are primarily quantitative in nature and have a cardinal scale. Stochastic dominance analysis and mathematical programming have their limitations in accommodating large amounts of qualitative information and completely fail to deal with ordinal and categorical data. This is not to say that other methods, e.g., scoring methods or the AHP are free of such restrictions, but due to their simple model structure these methods are more flexible in adjusting and transforming data in order to blend different benefit dimensions. The best method is surely the AHP in this respect.

Another consideration is that priority setting exercises should involve a critical mass of research alternatives to be assessed and compared. The greater the number of decision alternatives the more superior becomes formal optimisation of mathematical programming models. As long as the decision problem does not involve, say, more than 5 to 10 research alternatives then simple models or even manual checks may be sufficiently accurate.

Integration of the enhanced methods into the KARI priority setting procedure

To incorporate all or parts of the methods introduced in this study does not require a general modification of the KARI priority setting process. Risk analysis, however, requires minor modification in interrogation techniques for eliciting the ex-ante effects of research from scientists of a research program. Research experts must be made familiar with some basis probability theory and the notion of a probability distribution. Triangular probability distributions are simple to use and to specify. Complications arise when normal distributions and other theoretical distributions are involved which require to quantify some measures of variability. Yield increase, market prices, and research costs may be especially suitable to be integrated in risk analysis. Probability distributions for the rate of technology adoption may be harder to specify because of the time dynamic.

Crucial to risk analysis is a sound empirical basis from ex-post impact studies to determine the type of probability distributions used for different research parameters. KARI has started extensive field surveys in recent years for selected areas of the country (clusters) to study the impact of its new technologies on farmers' fields. This cross-farm information can serve as a valuable source for estimating some measures of variability and fitting empirical data to theoretical probability distributions. Official agricultural statistics in Kenya on prices, consumption, and production for major commodities are fairly comprehensive. However, these statistics provide highly aggregated data which are not particularly suitable for risk analysis purposes. Taking account of the KARI's capacity problems in priority setting the enhanced methods could be implemented in two steps. Even though research parameters may be defined as stochastic variables, KARI should start first with a traditional deterministic impact evaluation which would take a few days. Tentative results may then be reviewed and checked for internal consistency by selected members of the research program and the group of priority setting analysts. Simultaneously, plans for further analyses could be developed including the type of research projects for risk analyses and the set of planning aspects which are amenable to a mathematical programming model, such as predictions on short- and long-term program budgets, funding requirements for research centres, or distributional aspects of the research, and the like. Analysts should be given enough time to accomplish these analyses. Thus, evaluation workshops and the final stakeholder workshop where the final results and planning recommendations are presented must be scheduled accordingly.

Alternative views on risk and uncertainty in priority setting

Risk and uncertainty have been studied in this work from a rather technical and modelling perspective. A comprehensive coverage of risk and uncertainty aspects would have to include other perceptions of risks. In the first place, practitioners and research managers would pinpoint at the risk of research failure to generate worthwhile technologies. As mentioned earlier, the meaning of research success is not clear at all, and the way how research success can be made operational to impact evaluation may differ widely depending on the type of research. Further inquiry is also necessary to identify and study the major driving forces behind successful research. This would be beneficial to the reliability of any prospective research evaluation.

In the second place, risk in research is often viewed from the farmers' perspective. Besides the distributional consequences, the effects of research and modern technologies on the year-to-year variability in yield and farm income have been a major source of concern and criticism. A more accurate representation of risk on farm level in priority setting could be achieved by differentiation of the yield increase effects (and the probability distribution) by different farming systems and farm sizes. However, this does not necessarily indicate the particular risks on farmers' yield but is rather a measure for the variability between farms of the same system or size. The most promising way, though not the most accurate one, is to define a separate research objective, and to assess the impact of research on farm-level risks by subjective and qualitative measures, e.g., subjective scores.

A fundamentally different approach to investment analysis under uncertainty has been developed recently by DIXIT and PINDYCK (1994). They argue that traditional present value models such as those used in this study do not recognise the important qualitative and quantitative implications of the interaction between irreversibility, uncertainty and timing of an investment. The problem with standard profitability measures such as net present value is that they assume complete irreversibility and examine the investment over a full live, once and for all. In the process they ignore the option value in a given period for exiting the activity and putting the remaining resources to use in other activities. With irreversibility is meant the degree to which the capital invested is specific to the firm, a product or an industry, so that the capital becomes effectively tied to its original use. The salvage value for selling out parts of the investment very much depends on the degree of irreversibility.

BARTHAM et al. (1994, p. 4) argue that planning decisions based on present value calculations thus provide misleading information to decision makers because they neglect the effects of sunk costs and uncertainty. In the context of agricultural research, present value models discriminate against research projects which involve a large proportion of reversible capital, e.g., transportation facilities, tractors, combines, etc., and favour research projects which require large amounts of irreversible investments such as specialised laboratories. There are some persuasive arguments in favour of DIXIT's and PINIDYCK's measurement concept. One argument is a more accurate determination of the economic gains from research investments; the second is to reduce decision biases when selections among alternative research investments must be made that widely differ with respect to irreversibility. The third argument is that the degree of irreversibility may be a decisive factor for research institutions and farmers alike to explain why investments are made or not. However, implementing this measurement concept into the analysis of research investment is rather demanding. It requires incorporating series of future possible outcomes, and determining the option values of major assets at any given time of the investment process.

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Appendix A: Elicitation Results of the Dairy Research Projects

Table A-1: Elicitation results of research project 1: Technology generation

Project No. 1	Development and utilisation of calf feeds: Economics of feeding commercial feeds						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	0	1	2	0.5		87.50	1.095
HR 2	0	1	2	0.5		87.50	1.095
MR 1	0	1	2	0.5		87.50	1.095
MR 2	0	1	2	0.5		87.50	1.095
MR 3	0	1	2	0.5		87.50	1.095
LR 1	0	1	2	0.5		87.50	1.095

Table A-2: Elicitation results of research project 1: Adoption profile

Project No. 1	Development and utilisation of calf feeds: Economics of feeding commercial feeds			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	4.52
HR 2	3	1	4	4.52
MR 1	3	1	4	4.52
MR 2	3	1	4	4.52
MR 3	3	1	4	30.19
LR 1	3	1	4	30.19

Table A-3: Elicitation results of research project 1: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Nutritionist	2	1	24	24	24				1,200,000
Socio-economist	1	0.25	3	3	3				150,000
Veterinarian	1	0.25	3	3	6				200,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,550,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			M	M	M				
			348,905	556,605	1,733,830			Total	**4,189,340**

Table A-4: Elicitation results of research project 2: Technology generation

Project No. 2	Development and utilization of calf feeds: Development of locally available calf feeds						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	0	1.2	2.4	0.1		99.65	1.204
HR 2	0	1.2	2.4	0.1		99.65	1.204
MR 1	0	1.2	2.4	0.1		99.65	1.204
MR 2	0	1.2	2.4	0.1		99.65	1.204
MR 3	0	1.2	2.4	0.1		99.65	1.204
LR 1	0	1.2	2.4	0.1		99.65	1.204

Table A-5: Elicitation results of research project 2: Adoption profile

Project No. 2	Development and utilization of calf feeds: Development of locally available calf feeds			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	4	1	5	25.23
HR 2	4	1	5	25.23
MR 1	4	1	5	25.23
MR 2	4	1	5	9.75
MR 3	4	1	5	40.66
LR 1	4	1	5	40.66

Table A-6: Elicitation results of research project 2: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Nutritionist	2	1	24	24	24				1,200,000
Agronomist	1	0.5	6	6	6				300,000
Veterinarian	1	0.5; 0.33	6	6	4				266.666
Socio-economist	1	0.25	3	3	3				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,916,666**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			H	M	M				
			755,166	688,275	2,143,983			Total	**5,504,091**

Table A-7: Elicitation results of research project 3: Technology generation

Project No. 3	Development and utilization of diets of heifers and cows using locally available feedstuffs						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	6.25	25	45	12.5		94.62	26.27
HR 2	16.5	33	50	25		86.92	34.83
MR 1	12.5 (5)	20 (12.5)	30 (22.5)	15	15	32.14	17.2
MR 2	15 (7.5)	33.5 (26)	40 (32.5)	15	15	87.84	23.32
MR 3	12.5 (5)	30 (22.5)	42.5 (35)	12.75	15	88.56	22.21
LR 1	Not applicable						

Table A-8: Elicitation results of research project 3: Adoption profile

Project No. 3	Development and utilization of diets for heifers and cows using locally available feedstuffs			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	4	1	5	55.06
HR 2	4	1	5	54.55
MR 1	4	1	5	53.01
MR 2	4	1	5	54.55
MR 3	4	1	5	51.98
LR 1	Not applicable			

Table A-9: Elicitation results of research project 3: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Nutritionist	2	0.5; 1	12	24	24				1,000,000
Agronomist	1	1; 0.33; 0.5	12	4	6				366,666
Socio-economist	1	0.25	3	3	3				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,516,666**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			M	M	M				
			341,401	544,635	1,696,543			Total	**4,099,246**

Table A-10: Elicitation results of research project 4: Technology generation

Project No. 4	On-farm testing and adaptation of recommended forage production and utilisation techniques						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	Not applicable						
HR 2	22 (12)	44.67 (34.67)	66.67 (56.67)	20	20	93.68	35.60
MR 1	16.67 (6.67)	33.33 (23.33)	50 (40)	16.67	20	81.99	25.53
MR 2	11.33 (2.99)	33.33 (25)	53.33 (45)	13.33	16.67	88.44	26.22
MR 3	8.33 (-1.66)	16.67 (6.67)	33.33 (23.33)	8.33	20	54.04	12.72
LR 1	Not applicable						

Table A-11: Elicitation results of research project 4: Adoption profile

Project No. 4	Development and utilisation of calf feeds: Economics of feeding commercial feeds			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	Not applicable			
HR 2	3	1	4	46.80
MR 1	3	1	4	36.14
MR 2	3	1	4	48.10
MR 3	3	1	4	44.20
LR 1	Not applicable			

Table A-12: Elicitation results of research project 4: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Agronomist	2	1	24	24	24				1,200,000
Nutritionist	1	0.33	4	4	4				200,000
Socio-economist	1	0.25	3	3	3				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,550,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			H	L	H				
			610,700	139,190	2,600,745			Total	**4,900,635**

Table A-13: Elicitation results of research project 5: Technology generation

Project No. 5	Introduction and evaluation of forage varieties suitable for frost prone areas						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	16.67 (4.97)	33.33 (21.63)	53.33 (41.63	33.33	23.33	9.40	35.76
HR 2	Not applicable						
MR 1	Not applicable						
MR 2	Not applicable						
MR 3	Not applicable						
LR 1	Not applicable						

Table A-14: Elicitation results of research project 5: Adoption profile

Project No. 5	Introduction and evaluation of forage varieties suitable for frost prone areas			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	5	2	7	39.04
HR 2	Not applicable			
MR 1	Not applicable			
MR 2	Not applicable			
MR 3	Not applicable			
LR 1	Not applicable			

Table A-15: Elicitation results of research project 5: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Forage agronomist	2	0.5	12	12	12	12			800,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**800,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
				M	M				
				287,280	894,880			Total	**1,982,160**

Table A-16: Elicitation results of research project 6: Technology generation

Project No. 6	Improvement of feed quality through processing and forage legume utilisation						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	26.67 (10)	43.33 (26.67)	56.66 (40)	26.66	33.33	44.50	31.11
HR 2	26.67 (10)	46.67 (30)	66.67 (50)	20	33.33	87.50	31.90
MR 1	20 (6.66)	40 (26.66)	53.33 (40)	16.67	26.67	84.97	26.40
MR 2	13.33 (0)	40 (26.66)	56.67 (43.33)	13.33	26.67	84.62	25.96
MR 3	13.33 (0)	16.67 (3.33)	33.33 (20)	16.67	26.67	3.33	17.65
LR 1	Not applicable						

Table A-17: Elicitation results of research project 6: Adoption profile

Project No. 6	Improvement of feed quality through processing and forage legume utilisation			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	27.22
HR 2	3	1	4	24.01
MR 1	3	1	4	27.22
MR 2	3	1	4	35.36
MR 3	3	1	4	40.06
LR 1	Not applicable			

Table A-18: Elicitation results of research project 6: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline: Nutritionist	No. 6	(1/2 ; 1) 72	72	72	72	12			3,800,000
Average costs for 1 scientist / year	Discipline: All		200,000					Sub-total	**3,800,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
					M				
					4,250,680			Total	**8,050,680**

Table A-19: Elicitation results of research project 7: Technology generation

Project No. 7	Development of forage/food crop intercropping systems						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	12.5	25	40	12.5		100	25.83
HR 2	10 (7.5)	27.5 (25)	45 (42.5)	12.5	5	95.92	25.60
MR 1	12.5	20	35	12.5		100	22.50
MR 2	10	20	30	12.5		96.88	20.27
MR 3	Not applicable						
LR 1	Not applicable						

Table A-20: Elicitation results of research project 7: Adoption profile

Project No. 7	Development of forage/food crop intercropping systems			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	4	1	5	54.24
HR 2	4	1	5	53.62
MR 1	4	1	5	53.01
MR 2	4	1	5	55.00
MR 3	Not applicable			
LR 1	Not applicable			

Table A-21: Elicitation results of research project 7: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Agronomist	2	1	24	24	24				1,200,000
Nutritionist	1	0.33	4	4	4				200,00
Socio-economist	1	0.25	3	3	4				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,550,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			H	L	H				
			610,700	139,190	2,600,745			Total	**4,900,635**

Table A-22: Elicitation results of research project 8: Technology generation

Project No. 8	Improvement of feed conservation techniques and determination of feed availability year round						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	15 (2.5)	30 (17.5)	45 (32.5)	20	25	34.72	23.66
HR 2	15 (2.5)	30 (17.5)	45 (32.5)	20	25	34.72	23.66
MR 1	10 (-2.5)	27.5 (15)	42.5 (30)	15	25	46.15	20.00
MR 2	10 (-2.5)	27.5 (15)	42.5 (30)	15	25	46.15	20.00
MR 3	10(-2.5)	20 (7.5)	42.5 (30)	12.5	25	41.88	17.63
LR 1	Not applicable						

Table A-23: Elicitation results of research project 8: Adoption profile

Project No. 8	Improvement of feed conservation techniques and determination of feed availability year round			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	24.77
HR 2	3	1	4	24.77
MR 1	3	1	4	24.77
MR 2	3	1	4	43.94
MR 3	3	1	4	63.96
LR 1	Not applicable			

Table A-24: Elicitation results of research project 8: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Agronomist	2	1	24	24	24				1,200,000
Nutritionist	1	0.5	6	6	6				300,000
Socio-economist	1	0.25	3	3	3				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,650,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
				field trials	equipment	transportation			
				L	H	M			
				92,895	1,036,860	1,845,690		Total	**4,625,445**

Table A-25: Elicitation results of research project 9: Technology generation

Project No. 9	Development of forage legume seed production technology						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	not applicable						
HR 2	not applicable						
MR 1	not applicable						
MR 2	16.67 (10)	33.33 (26.66)	46.67 (40)	16.67	13.33	91.10	26.64
MR 3	13.33 (6.66)	26.67 (20)	40 (33.33)	13.33	13.33	87.50	21.27
LR 1	not applicable						

Table A-26: Elicitation results of research project 9: Adoption profile

Project No. 9	Development of forage legume seed production technology			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	Not applicable			
HR 2	Not applicable			
MR 1	Not applicable			
MR 2	3	1	4	54.24
MR 3	3	1	4	55.68
LR 1	Not applicable			

Table A-27: Elicitation results of research project 9: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Agronomist	2	1	24	24	24	24			1,600,000
Plant breeder	1	0.25	3	3	3	3			200,000
Socio-economist	1	0.25; 0.5	3	3	6	6			300,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**2,100,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials		equipment		transportation		
			M		M		M		
			472,710		754,110		2,349,060	Total	**5,675,880**

Table A-28: Elicitation results of research project 10: Technology generation

Project No. 10	Development of appropriate calf housing and studies on *HELMINTHS* disease						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	0 (-1.5)	6 (4.5)	10 (8.5)	5	3	30.63	6.03
HR 2	0 (-1.5)	6 (4.5)	10 (8.5)	5	3	30.63	6.03
MR 1	0 (-1.5)	6 (4.5)	10 (8.5)	5	3	30.63	6.03
MR 2	0 (-1.5)	6 (4.5)	10 (8.5)	5	3	30.63	6.03
MR 3	0 (-1.5)	6 (4.5)	10 (8.5)	5	3	30.63	6.03
LR 1	0 (-1.5)	6 (4.5)	10 (8.5)	5	3	30.63	6.03

Table A-29: Elicitation results of research project 10: Adoption profile

Project No. 10	Development of appropriate calf housing and studies on *HELMINTHS* disease			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	42.43
HR 2	3	1	4	42.43
MR 1	3	1	4	42.43
MR 2	3	1	4	42.43
MR 3	3	1	4	42.43
LR 1	3	1	4	42.43

Table A-30: Elicitation results of research project 10: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Agriculturalist	1	0.25; 1; 1	3	1	1				83,333
Veterinarian	1	0.25	3	3	3				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**233,333**

Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:

	field trials	equipment	transportation		
	L	L	H		
	13,136	20,953	391,510	Total	**658,933**

Table A-31: Elicitation results of research project 11: Technology generation

Project No. 11	Studies of cow fertility problems, causes and possible solutions						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	7 (3.5)	15 (11.5)	25 (21.5)	11	7	60.94	14.52
HR 2	7 (3.5)	15 (11.5)	25 (21.5)	11	7	60.94	14.52
MR 1	7 (3.5)	15 (11.5)	25 (21.5)	11	7	60.94	14.52
MR 2	7 (3.5)	15 (11.5)	25 (21.5)	11	7	60.94	14.52
MR 3	7 (3.5)	15 (11.5)	25 (21.5)	11	7	60.94	14.52
LR 1	7 (4)	15 (12)	25 (22)	11	6	65.97	14.73

Table A-32: Elicitation results of research project 11: Adoption profile

Project No. 11	Studies of cow fertility problems, causes and possible solutions			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	51.32
HR 2	3	1	4	51.32
MR 1	3	1	4	51.32
MR 2	3	1	4	51.32
MR 3	3	1	4	51.32
LR 1	3	1	4	51.32

Table A-33: Elicitation results of research project 11: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Nutritionist	1	0.25	3	3	3				150,000
Physiologist	1	0.25	3	3	3				150,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**300,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			L	L	L				
			16,890	26,940	503,370			Total	**847,200**

Table A-34: Elicitation results of research project 12: Technology generation

Project No. 12	On-farm testing of ECF-immunisation						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	3 (2.5)	5(4.5)	7 (6.5)	3	1	96.88	4.55
HR 2	3 (2.5)	5(4.5)	7 (6.5)	3	1	96.88	4.55
MR 1	3 (2.5)	5(4.5)	7 (6.5)	3	1	96.88	4.55
MR 2	3 (2.5)	5(4.5)	7 (6.5)	3	1	96.88	4.55
MR 3	3 (2.5)	5(4.5)	7 (6.5)	3	1	96.88	4.55
LR 1	3 (2.5)	5(4.5)	7 (6.5)	3	1	96.88	4.55

Table A-35: Elicitation results of research project 12: Adoption profile

Project No. 12	On-farm testing of ECF-immunisation			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	39.81
HR 2	3	1	4	39.81
MR 1	3	1	4	39.81
MR 2	3	1	4	39.81
MR 3	3	1	4	39.81
LR 1	3	1	4	39.81

Table A-36: Elicitation results of research project 12: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Veterinarian	1	0.2	3	2	3				133,333
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**133,333**

Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:

	field trials	equipment	transportation		
	L	L	H		
	7,506	11,973	223,720	Total	**376,533**

Table A-37: Elicitation results of research project 13: Technology generation

Project No. 13	Practical mastitis control						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	0.5 (0.25)	1.5 (1.25)	3 (2.75)	1	0.5	77.50	1.61
HR 2	0.5 (0.25)	1.5 (1.25)	3 (2.75)	1	0.5	77.50	1.61
MR 1	0.5 (0.25)	1.5 (1.25)	3 (2.75)	1	0.5	77.50	1.61
MR 2	0.5 (0.25)	1.5 (1.25)	3 (2.75)	1	0.5	77.50	1.61
MR 3	0.5 (0.25)	1.5 (1.25)	3 (2.75)	1	0.5	77.50	1.61
LR 1	0.5 (0.25)	1.5 (1.25)	3 (2.75)	1	0.5	77.50	1.61

Table A-38: Elicitation results of research project 13: Adoption profile

Project No. 13	Practical mastitis control			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	3	1	4	54.30
HR 2	3	1	4	54.30
MR 1	3	1	4	54.30
MR 2	3	1	4	54.30
MR 3	3	1	4	54.30
LR 1	3	1	4	54.30

Table A-39: Elicitation results of research project 13: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Veterinarian	1	0.5; 0.25	6	3	3				200,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**200,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			H	L	H				
			78,800	17,960	233,580			Total	**530,340**

Table A-40: Elicitation results of research project 14: Technology generation

Project No. 14	Indigenous disease control methods (ethnovet)						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	0 (-0.5)	5 (4.5)	10 (9.5)	1	1	95.50	4.69
HR 2	0 (-0.5)	5 (4.5)	10 (9.5)	1	1	95.50	4.69
MR 1	0 (-0.5)	5 (4.5)	10 (9.5)	1	1	95.50	4.69
MR 2	0 (-0.5)	5 (4.5)	10 (9.5)	1	1	95.50	4.69
MR 3	0 (-0.5)	5 (4.5)	10 (9.5)	1	1	95.50	4.69
LR 1	0 (-0.5)	5 (4.5)	10 (9.5)	1	1	95.50	4.69

Table A-41: Elicitation results of research project 14: Adoption profile

Project No. 14	Indigenous disease control methods (ethnovet)			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	4	3	7	59.53
HR 2	4	3	7	59.53
MR 1	4	3	7	59.53
MR 2	4	3	7	59.53
MR 3	4	3	7	59.53
LR 1	4	3	7	59.53

Table A-42: Elicitation results of research project 14: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Botanist	1	0.33	4	4					133.333
Anthropologist	1	0. 33; 0.5; 0.2	4	4	6	6	3	3	433,333
Veterinarian	1	0. 33; 0.5; 0.2	4	4	6	6	3	3	433,333
Pharmacologist		0. 33; 0.5; 0.2					10	10	333,333
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**1,333,333**

Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:

	field trials	equipment	transportation		
	H	H	H		
	525,333	837,866	1,557,053	Total	**4,253,586**

Table A-43: Elicitation results of research project 15: Technology generation

Project No. 15	Development of alternative or improved delivery system for assisting health service						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	10 (7.5)	25 (22.5)	40 (37.5)	10	5	98.61	22.69
HR 2	10 (7.5)	25 (22.5)	40 (37.5)	10	5	98.61	22.69
MR 1	10 (7.5)	25 (22.5)	40 (37.5)	10	5	98.61	22.69
MR 2	10 (7.5)	25 (22.5)	40 (37.5)	10	5	98.61	22.69
MR 3	10 (7.5)	25 (22.5)	40 (37.5)	10	5	98.61	22.69
LR 1	10 (7.5)	25 (22.5)	40 (37.5)	10	5	98.61	22.69

Table A-44: Elicitation results of research project 15: Adoption profile

Project No. 15	Development of alternative or improved delivery system for assisting health service			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	6	3	9	33.93
HR 2	6	3	9	33.93
MR 1	6	3	9	33.93
MR 2	6	3	9	33.93
MR 3	6	3	9	33.93
LR 1	6	3	9	33.93

Table A-45: Elicitation results of research project 15: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Economist	2	10/12	20	20	20	20	20	20	2,000,00
Veterinarian	2	10/12	20	20	20	20	20	20	2,000,00
Anthropologist	2	10/12	20	20	20	20	20	20	2,000,00
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**6,000,00**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			L	M	H				
			337,800	2,154,600	7,006,740			Total	**15,499,0**

Table A-46: Elicitation results of research project 16: Technology generation

Project No. 16	Development of more productive breeds for zero/ semi-zero grazing systems						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	5 (3.75)	10 (8.75)	15 (13.75)	0	2.5	100.00	8.75
HR 2	5 (3.75)	10 (8.75)	15 (13.75)	0	2.5	100.00	8.75
MR 1	5 (3.75)	10 (8.75)	15 (13.75)	0	2.5	100.00	8.75
MR 2	5 (3.75)	10 (8.75)	15 (13.75)	0	2.5	100.00	8.75
MR 3	5 (3.75)	10 (8.75)	15 (13.75)	0	2.5	100.00	8.75
LR 1	5 (3.75)	10 (8.75)	15 (13.75)	0	2.5	100.00	8.75

Table A-47: Elicitation results of research project 16: Adoption profile

Project No. 16	Development of more productive breeds for zero/ semi-zero grazing systems			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	6	4	10	45.76
HR 2	6	4	10	45.76
MR 1	6	4	10	45.76
MR 2	6	4	10	45.76
MR 3	6	4	10	45.76
LR 1	6	4	10	45.76

Table A-48: Elicitation results of research project 16: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Animal breeder	1	10/12	10	10	10	10	10	40	1,500,000
Veterinarian	1	0.33	4	4	4	4	4	16	600,000
Nutritionist	1	0.25	3	3	3	3	3	12	450,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**2,550,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			H	H	H				
			1,004,700	1,602,420	2,852,430			Total	**8,009,550**

Table A-49: Elicitation results of research project 17: Technology generation

Project No. 17	Development of more productive breeds for free grazing systems						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	Not applicable						
HR 2	Not applicable						
MR 1	Not applicable						
MR 2	Not applicable						
MR 3	Not applicable						
LR 1	5 (3)	15 (13)	25 (23)	10	4	77.73	15.39

Table A-50: Elicitation results of research project 17: Adoption profile

Project No. 17	Development of more productive breeds for free grazing systems			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	Not applicable			
HR 2	Not applicable			
MR 1	Not applicable			
MR 2	Not applicable			
MR 3	Not applicable			
LR 1	6	4	10	34.47

Table A-51: Elicitation results of research project 17: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Animal breeder	1	10/12	10	10	10	10	10	40	1,500,000
Veterinarian	1	0.33	4	4	4	4	4	16	600,000
Nutritionist	1	0.25	3	3	3	3	3	12	450,000
Average costs for 1 scientist / year		Discipline: All		200,000				Sub-total	**2,550,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
			H	H	H				
			1,004,700	1,602,420	2,852,430			Total	**8,009,550**

Table A-52: Elicitation results of research project 18: Technology generation

Project No. 18	Policy environment study of milk marketing (government option)						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	4	8	25	13.35		37.67	16.83
HR 2	4	8	25	13.35		37.67	16.83
MR 1	4	8	25	13.35		37.67	16.83
MR 2	4	8	25	13.35		37.67	16.83
MR 3	4	8	25	13.35		37.67	16.83
LR 1	4	8	25	13.35		37.67	16.83

Table A-53: Elicitation results of research project 18: Adoption profile

Project No. 18	Policy environment study of milk marketing (government option)			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	1	2	3	50
HR 2	1	2	3	50
MR 1	1	2	3	50
MR 2	1	2	3	50
MR 3	1	2	3	50
LR 1	1	2	3	50

Table A-54: Elicitation results of research project 18: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Data entry clark	1	1; 0.75	12	9	9	9	9		560,000
Manager	1	0.25	3	3	3	3	3		175,000
Socio-economist	1	1; 0.5	12	6	6	6	6		420,000
Programmer	1	0.5; 0.25	6	3	3	3	3		210,000
Average costs for 1 scientist / year		Discipline: All		140,000				Sub-total	**1,365,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
				L	M				
				1500,000	390,000			Total	**1,905,000**

Table A-55: Elicitation results of research project 19: Technology generation

Project No. 19	Policy environment study of milk marketing (private option)						
	Yield Increase (%)						
Agro-ecological zone	Lowest %	Most likely %	Highest %	Dissemination Threshold %	Production cost increase %	Probability of research success %	Conditional net yield increase % ....
HR 1	4.4	8.8	27.5	12.75		50.37	17.07
HR 2	4.4	8.8	27.5	12.75		50.37	17.07
MR 1	4.4	8.8	27.5	12.75		50.37	17.07
MR 2	4.4	8.8	27.5	12.75		50.37	17.07
MR 3	4.4	8.8	27.5	12.75		50.37	17.07
LR 1	4.4	8.8	27.5	12.75		50.37	17.07

Table A-56: Elicitation results of research project 19: Adoption profile

Project No. 19	Policy environment study of milk marketing (private option)			
Agro-ecological zone	Research lag years	Time to dissemination years	Begin of dissemination years	Adoption level after 30 years %
HR 1	1	2	3	50
HR 2	1	2	3	50
MR 1	1	2	3	50
MR 2	1	2	3	50
MR 3	1	2	3	50
LR 1	1	2	3	50

Table A-57: Elicitation results of research project 19: Research costs

Required scientists		part time (1/2) full time (1)	year 1	year 2	year 3	year 4	year 5	Remaining years	Total costs (KSh)
			months/ year	months/ year	months/ year	months/ year	months/ year	months/ year	
Discipline:	No.	(1/2 ; 1)							
Enumerator	18	1	216						1,800,000
Socio-economist	3	0.5	18						234,000
Average costs for 1 scientist / year		Discipline:	Enum = socio-econ..=		140,000 156,000			Sub-total	**2,034,000**
Other costs: In relation to the costs for scientists this project is light (L), medium (M) or heavy (H) in:									
			field trials	equipment	transportation				
				L	M				
				182,653	1,170,000			Total	**3,386,653**

Appendix B: Bootstrap Results

Figure B-1: Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 3 and Rp 4

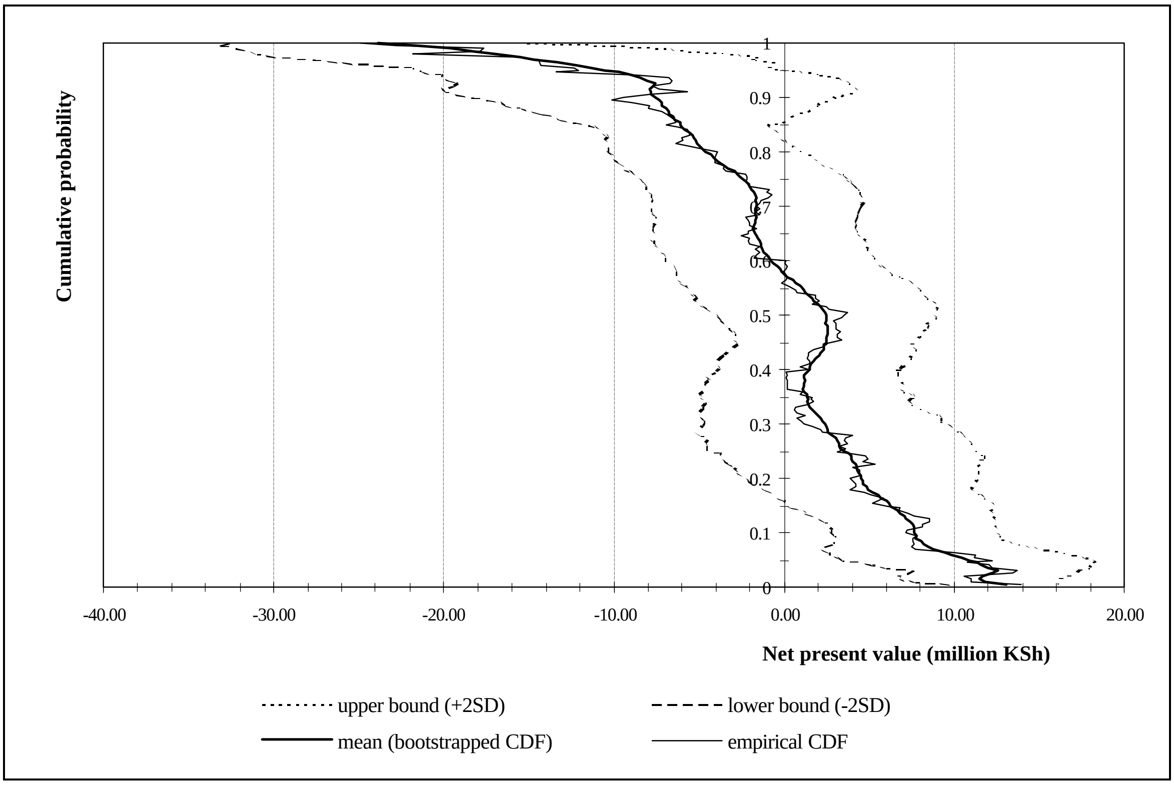


Figure B-2: Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 3 and Rp 6

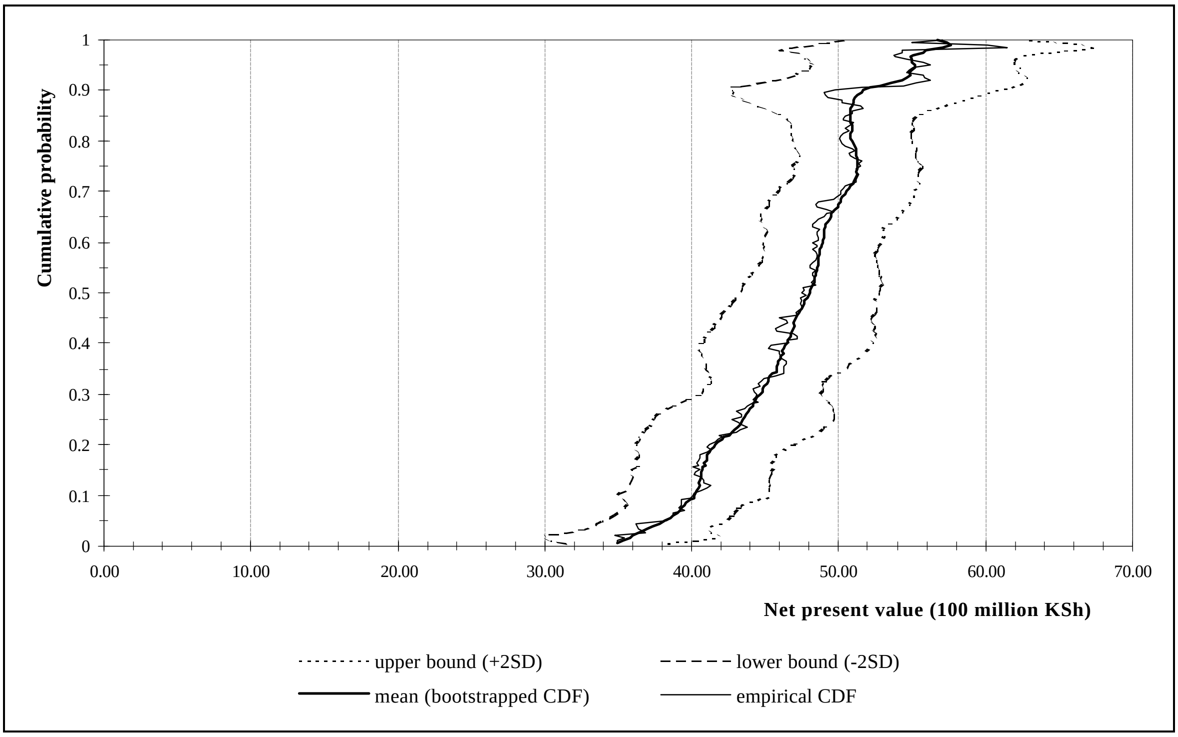


Figure B-3: Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 3 and Rp 19

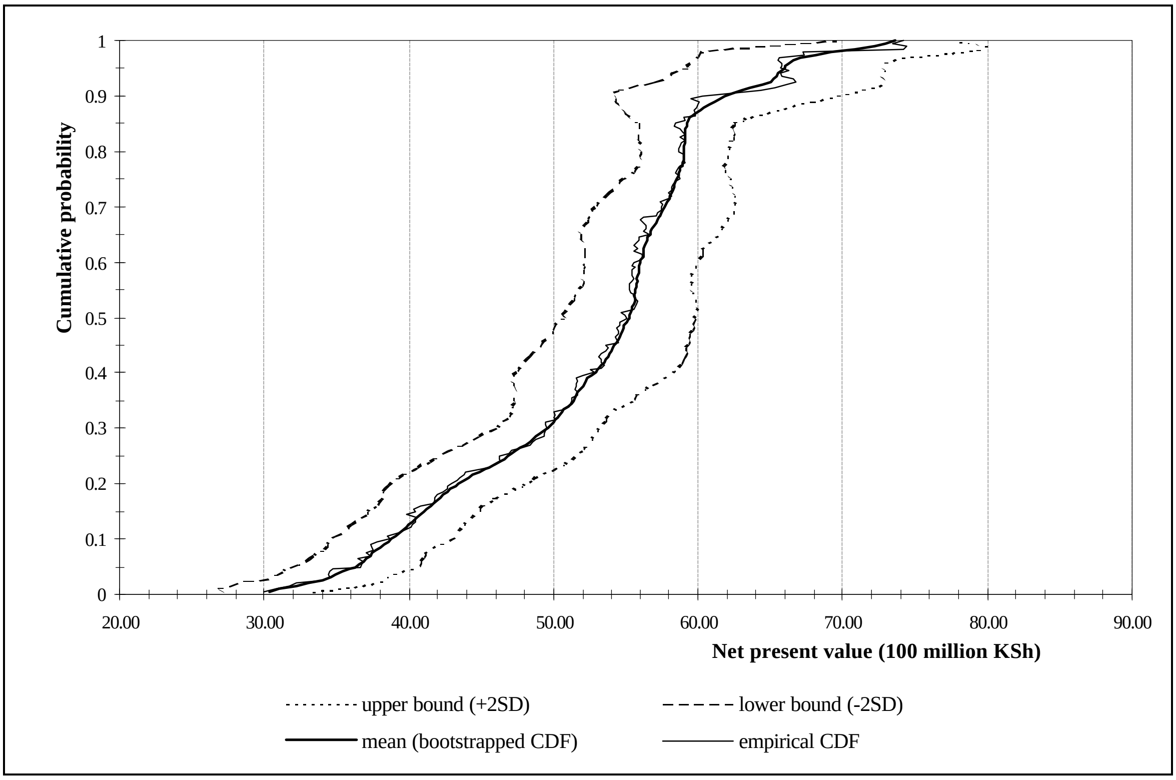


Figure B-4: Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 4 and Rp 6

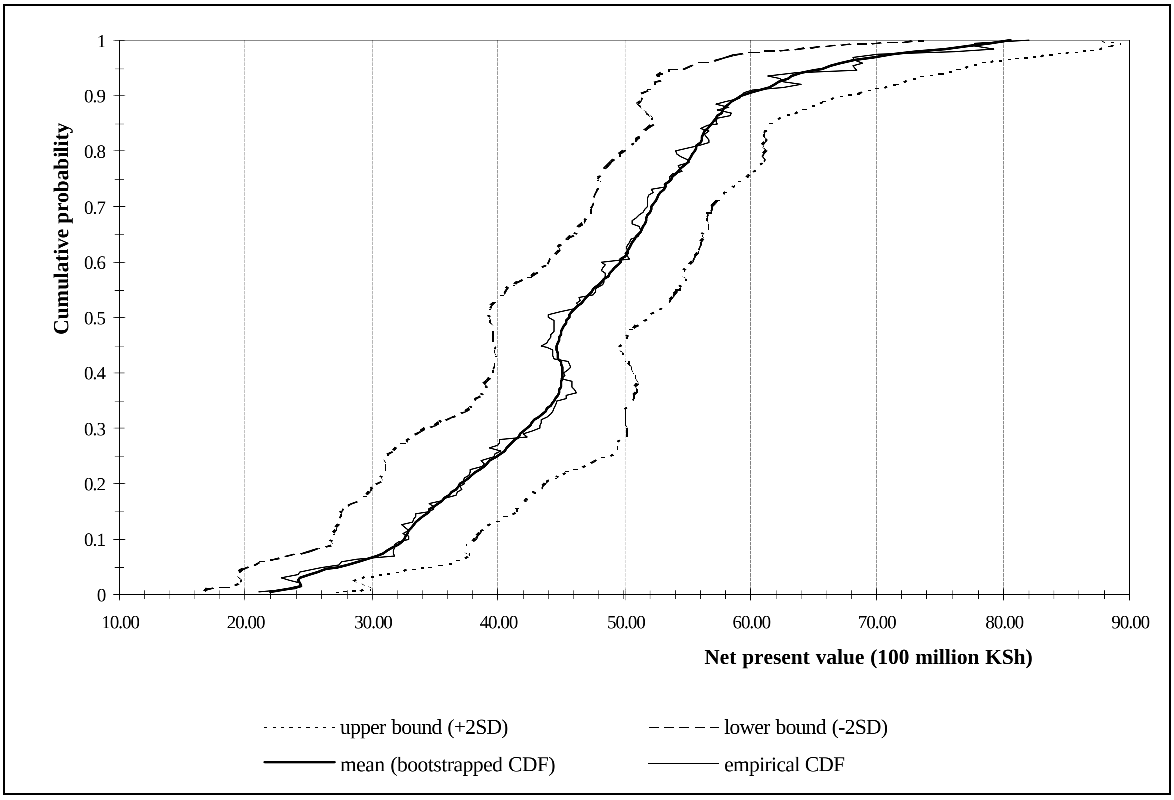


Figure B-5: **Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 4 and Rp 19**

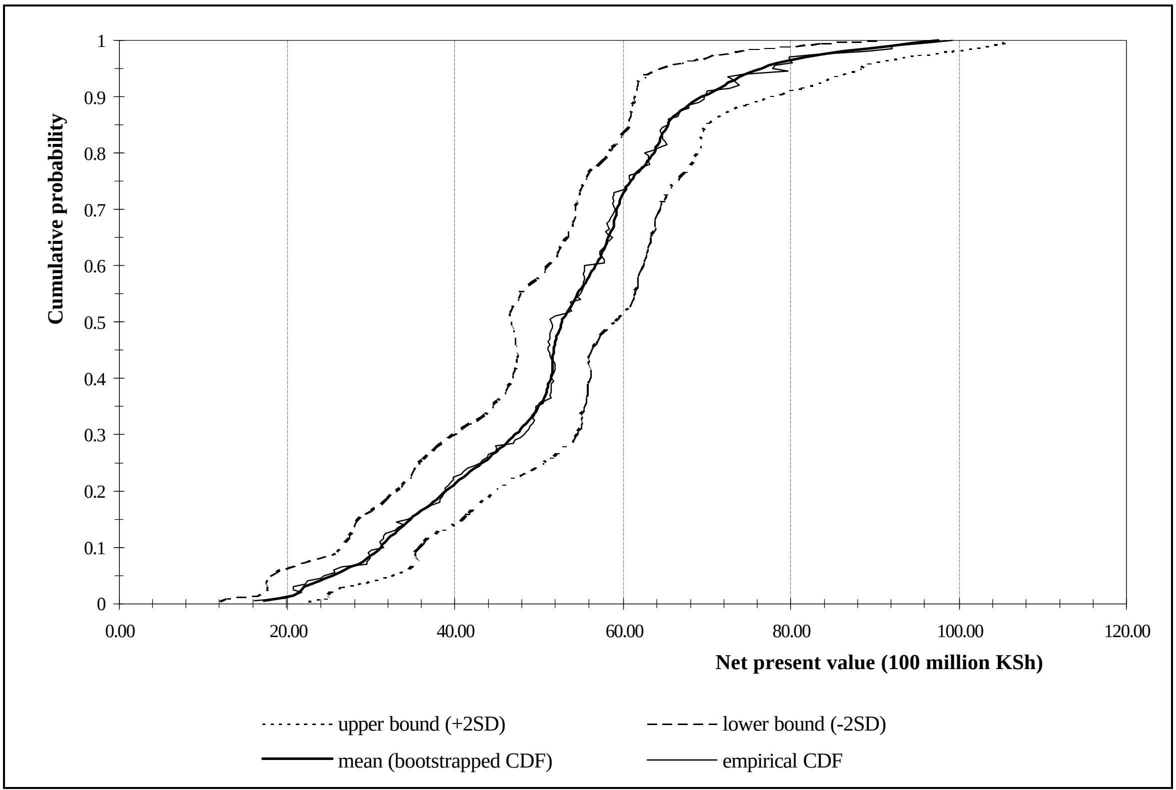


Figure B-6: **Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 6 and Rp 7**

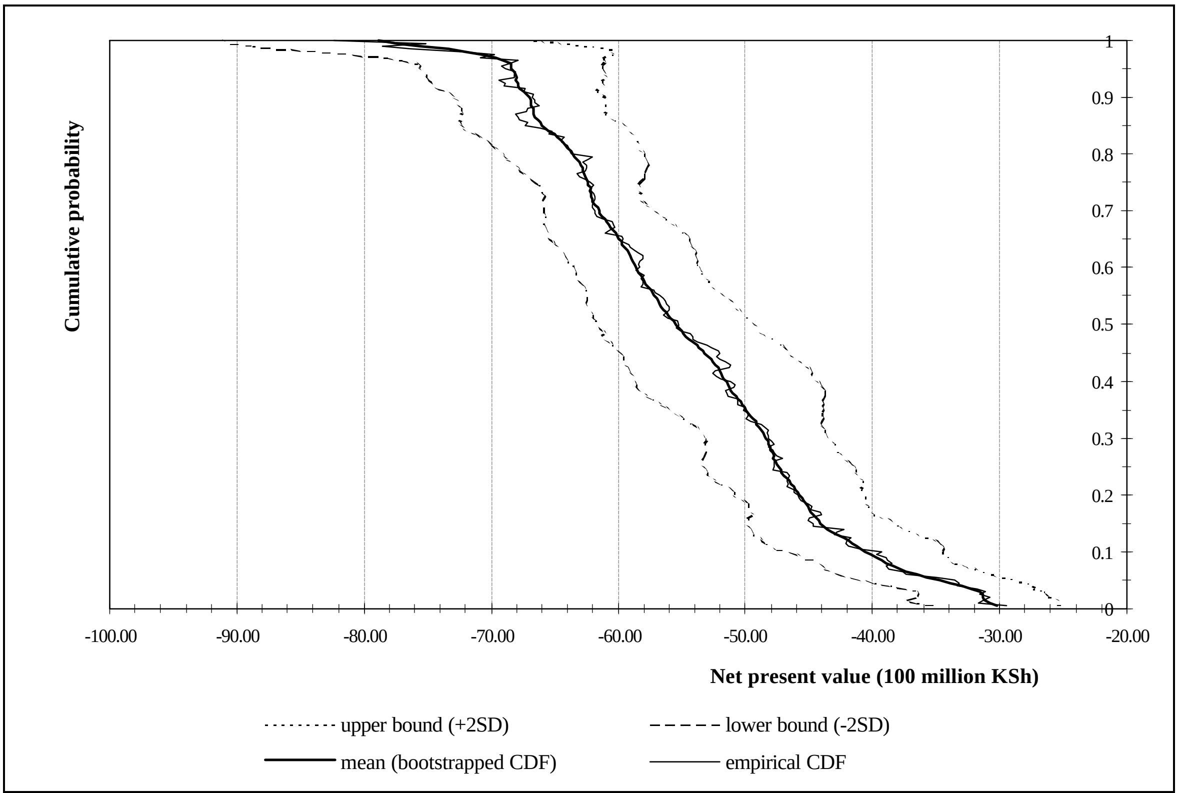
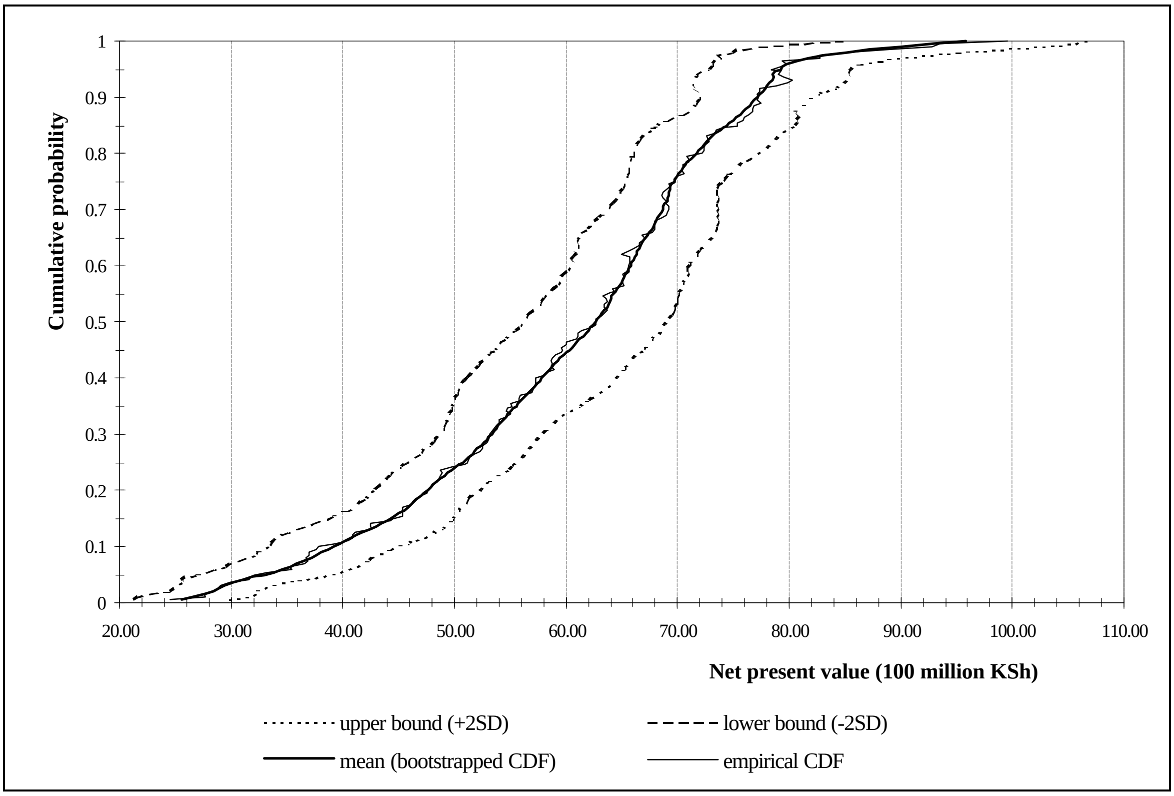


Figure B-7: **Confidence bands (α = 95%) for the differences between empirical cumulative distribution functions (CDFs) for Rp 7 and Rp 19**



Appendix C Induced Rank Correlation

Appendix C-1: Description of the IMAN and CONOVER Method of Induced Rank Correlation Among Multiple Input Variables

The IMAN and CONOVER method of induced rank correlation is based on the following proposition:

Suppose that a random input vector X has a correlation matrix I. That is, the elements of X are uncorrelated. Let C be the desired rank correlation matrix of some transformation of X. Because C is positive definite and symmetric, C may be written as $C = PP^T$ (Cholesky factorisation), where P is a lower triangular matrix. Then, the transformed vector XP' has the desired correlation matrix C. This is the theoretical basis. The IMAN and CONOVER's approach does not build correlation on the input values directly but induces the desired rank correlation on the "van der Waerden scores" Φ^{-1} (i/N-1), where Φ^{-1} is the inverse function of the of the standard normal distribution function.

The use of van der Waerden scores results in naturally looking pairwise plots, while other scores (e.g., scores derived from the rank of the input values) usually generate bivariate scatter plots, which are pinched in the middle and spread out in the tails. However, for ease of exposition, we used, instead of the van der Waerden scores, the ranks from the input values as a simplification of the procedure. As it depicted from the scatter plot for two correlated variables (distribution 5 and 6) in appendix A-3.2, the pairs are slightly pinched in the middle and spread out in the tails but still may be tolerable for the purpose of induced correlation.

The objective is for the Spearman rank correlation matrix M of the input vectors to be close to the target rank correlation matrix C supplied by the user while preserving the marginal distributions and the properties of the sampling scheme used to obtain the input vectors. Let the number of input variables be denoted by k and let n be the sample size. Let R be an $n \times k$ matrix whose columns represent the ranking scores of the input values taking the integer values between 1 and n. Further, let C be the user supplied $k \times k$ target rank correlation matrix, and let P be a $k \times k$ matrix such that $PP^T = C$. It is suggested, that the Cholesky factorisation scheme may be used to obtain a lower triangular matrix P. Multiplication of the entire matrix R by P^T, $RP^T = R^*$, gives a $n \times k$ matrix R^* whose rank correlation matrix M should be close to C. For the rank correlation matrix of the input values to be approximately equal to C, the values in each column (each input variable) of the $n \times k$ input matrix X are rearranged, so that they will have the same ordering as the correspondent columns of R^*. Thus the input values have the same sample rank correlation matrix that R^* has.

In many cases, the correlation matrix M is not close enough to C. While the non-zero target correlations agree closely with the desired correlation values of C, some of the zero target correlations from C are rather large in M. The primary reason for this variation is that the sample correlation matrix T (the Pearson correlation coefficient and not the Spearman rank correlation coefficient) associated with X or R may not exactly equal to I which means some variables are correlated. As a result, this random variation in T carries through the transformation, so that the sample correlation matrix of R^* (= RP^T) may not be close enough to C for all applications of this procedure. Only when the correlation matrix of X or R is I then the rank correlation matrix M associated with R^* would be approximately equal to C.

This concern led to the development of a variance reduction techniques in which the transformation matrix P is adjusted so that the final sample correlation matrix M^* will be much closer to C than M. In order to avoid the problem of M associated with R^* not being close enough to C a $k \times k$ matrix S must be found such that $STS^T = C$ where T is the sample correlation matrix associated with R.

The Cholesky factorisation may be used to find first a lower triangular matrix Q such that $T = QQ^T$. This along with the fact that $C = PP^T$ allows the equation involving S to be rewritten as $SQQ^TS^T = PP^T$ for which one solution is $SQ = P$ or $S = PQ^{-1}$. Note that S is also a lower triangular matrix.. Then the matrix $R_B^* = RS^T$ has a correlation matrix M^* that is approximately equal to C. Finally, the Spearman rank correlation matrix M^* of R_B^* can be found and compared with M and the desired rank correlation matrix C. From the numerical example, this comparison shows the non-zero target correlations of M^* again to be in close agreement with the desired C values while the zero target correlation are as a whole much closer to zero than appeared in the matrix M.

In a final step the columns of the initial input variables in matrix X are to be rearranged to receive X_B^* , so that they have the same order (rank) as the correspondent columns in R_B^*. Thus, the sample Spearman rank correlation of the final input vector X_B^* will be the same as the sample Spearman rank correlation M^* of R_B^*. Also, the identity of the original marginal distributions on the input variables has been maintained, as the procedure explained above merely provides a means for pairing the variables but does not change the numbers themselves.

Appendix C-2: Numerical Example of the IMAN and CONOVER Method of Induced Rank Correlation

C					
1	0	0	0	0	0
0	1	0	0	0	0
0	0	1	0	0	0
0	0	0	1	0.750	-0.700
0	0	0	0.750	1	-0.950
0	0	0	-0.700	-0.950	1

P					
1	0	0	0	0	0
0	1	0	0	0	0
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0.750	0.661	0
0	0	0	-0.700	-0.642	0.312

T					
1	-0.217	-0.134	-0.579	-0.032	0.071
-0.217	1	-0.220	-0.316	-0.035	0.059
-0.134	-0.220	1	-0.020	0.144	-0.203
-0.579	-0.316	-0.020	1	-0.041	-0.241
-0.032	-0.035	0.144	-0.041	1	-0.176
0.071	0.059	-0.203	-0.241	-0.176	1

Q					
1	0	0	0	0	0
-0.217	0.976	0	0	0	0
-0.134	-0.255	0.958	0	0	0
-0.579	-0.452	-0.221	0.642	0	0
-0.032	-0.042	0.135	-0.075	0.987	0
0.071	0.076	-0.182	-0.321	-0.172	0.907

S					
1	0	0	0	0	0
0.222	1.024	0	0	0	0
0.199	0.272	1.044	0	0	0
1.1279	0.815	0.360	1.559	0	0
0.912	0.657	0.194	1.247	0.670	0
-0.741	-0.531	-0.080	-0.989	-0.591	0.343

M*					
1	-0.059	-0.056	-0.114	-0.002	0.045
-0.059	1	0.021	-0.003	0.018	-0.014
-0.056	0.021	1	0.056	-0.029	0.012
-0.114	-0.003	0.056	1	0.813	-0.740
-0.002	0.018	-0.029	0.813	1	-0.923
0.045	-0.014	0.012	-0.740	-0.923	1

X Input

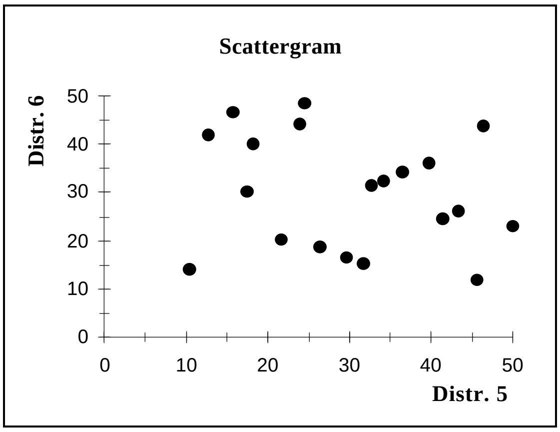
Distr. 1	Distr. 2	Distr. 3	Distr. 4	Distr. 5	Distr. 6
17.937	12.318	45.200	44.261	41.418	24.418
48.587	25.946	21.958	18.811	23.908	44.065
41.181	17.360	48.069	14.131	29.623	16.336
10.628	38.460	33.145	38.419	36.528	34.174
38.164	37.139	11.482	20.109	21.722	20.282
36.665	23.575	37.913	22.886	32.617	31.340
35.464	46.948	43.324	24.464	43.262	26.088
14.291	29.293	39.583	40.602	10.501	13.871
44.291	27.352	29.599	27.511	49.996	22.906
25.652	31.625	16.348	32.532	39.801	36.057
32.482	21.010	25.486	49.443	12.803	41.850
13.068	34.775	18.548	37.021	15.835	46.716
42.168	15.793	14.820	29.017	34.178	32.274
21.487	41.857	13.761	43.190	26.481	18.571
29.093	18.903	47.400	31.174	24.537	48.314
47.880	32.549	23.916	12.241	18.252	39.949
27.125	45.790	31.782	35.484	31.693	15.189
19.865	49.743	27.750	10.806	46.425	43.721
30.533	43.445	41.132	16.628	17.520	29.977
23.130	10.937	35.527	46.562	45.597	11.703

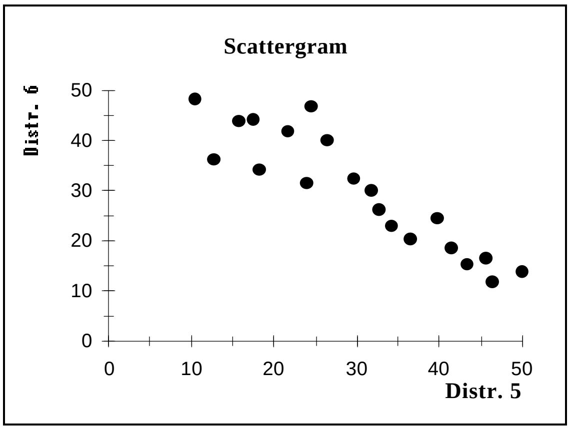
X_B^* Output

Distr. 1	Distr. 2	Distr. 3	Distr. 4	Distr. 5	Distr. 6
17.937	12.318	41.132	32.532	36.528	20.282
48.587	27.352	23.916	29.017	26.481	39.949
41.181	18.903	47.400	12.241	12.803	36.057
10.628	34.775	33.145	35.484	34.178	22.906
38.164	38.460	14.820	20.109	23.908	31.340
36.665	23.575	39.583	18.811	29.623	32.274
35.464	49.743	48.069	44.261	49.996	13.871
14.291	25.946	37.913	37.021	18.252	34.174
44.291	31.625	31.782	40.602	46.425	11.703
25.652	29.293	16.348	22.886	32.617	26.088
32.482	21.010	21.958	49.443	39.801	24.418
13.068	32.549	18.548	14.131	10.501	48.314
42.168	15.792	11.482	27.511	31.693	29.977
21.487	41.857	13.761	43.190	41.418	18.571
29.093	17.360	43.324	31.174	24.537	46.716
47.880	37.139	25.486	16.628	17.520	44.065
27.125	45.790	35.527	46.562	45.597	16.336
19.865	46.948	29.599	10.806	21.722	41.850
30.533	43.445	45.200	24.464	15.835	43.721
23.130	10.937	27.750	38.419	43.262	15.189

Initial correlation between distribution. 5 and 6: (Pearson r (T)= -0.176)

Induced correlation between distribution 5 and 6: desired level r (C) = -0.950; achieved level Spearman r (M^*) = -0.923





Appendix D Numerical Recipes in Visual Basic for Applications

Appendix D-1: Routine for the Shell's Sorting Procedure for Multiple Variables (Variant of the Straight Insertion Method)

Sorting data in ascending or descending order is important for generating cumulative probabilities, cumulative plots, and developing own stochastic dominance procedures.

```
Option explicit
Sub shell's_sorting_routine()
Dim i, j, n, m, k, inc As Integer
Dim data(), v As Single
'  DEFINES DATA ARRAY (N = NUMBER OF OBSERVATION PER VARIABLE, K = NUMBER OF VARIABLES)
n = 200: k = 10: inc = 1
ReDim data(n, k)
'  READS DATA ARRAY FROM THE SPREADSHEET 'TABELLE1' IN RANGE (B3: K202)
For j = 1 To k: For i = 1 To n
data(i, j) = Worksheets("Tabelle1").Cells(2 + i, j + 1)
Next i: Next j
' END READING
' BEGIN SORTING IN ASCENDING ORDER
For j = 1 To k
inc = 1
While inc < n
inc = (3 * inc) + 1
Wend
While inc > 1
inc = inc / 3
For i = inc + 1 To n
v = data(i, j): m = i
While data(m - inc, j) > v
data(m, j) = data(m - inc, j): m = m - inc
If m < inc Then
Exit For
End If
Wend
data(m, j) = v
Next i: Wend: Next j
'  END SORTING
'  WRITES SORTED DATA TO SPREADSHEET 'TABELLE2' IN RANGE (B3:K202)
For j = 1 To k: For i = 1 To n
Worksheets("Tabelle2").Cells(2 + i, 1 + j) = data(i, j)
Next i: Next j
' END WRITING
End Sub
```

Appendix D-2: Routine for Monte Carlo Sampling From a Triangular Probability Distribution

```
Option Explicit
Sub Monte_Carlo_simulation()
Dim k, kl, km, kh, u As Single
Dim i, n, As Integer
With Application
        .Calculation = xlManual
End With
‘  DEFINE THE DISTRIBUTION (KL = LOWEST, KM = MOST LIKELY, AND KH = HIGHEST % YIELD
   INCREASE)
kl = 10;km = 30: kh = 50
‘ N = NUMBER OF SAMPLES DRAWN
n = 100
For i = 1 To n
Randomize
‘ DRAWS 100 RANDOM NUMBERS U GENERATED FROM A UNIFORM (0,1) DISTRIBUTION
u = Rnd
'  INVERSE TRANSFORMATION OF THE TRIANGULAR CDF
‘  SEPARATES THE TWO INVERSE TRANSFORMATION EQUATIONS DEPENDING ON WHETHER K < OR > KM
If u < (km - kl) / (kh - kl) Then
‘  CALUCLATES RANDOM VARIATES K
k = kl + ((u * (kh - kl) * (km - kl)) ^ 0.5)
Else
k = kh - (((1 - u) * (kh - kl) * (kh - km)) ^ 0.5)
End If
Next i
Calculate
End Sub
```

Appendix D-3: Routine for Latin-hypercube Sampling From a Triangular Probability Distribution Truncated at the Dissemination Threshold

```
Option Explicit
Sub Latin_hypercube_ sampling()
Dim sample, kl, km, kh, kt, u, k, ut, strata_size As Single
Dim i, n, z, strata As Integer
Dim check_matrix(), end_matrix() As Single
Dim user_table As Variant
Set user_table = Worksheets("Tabelle1")
With Application
        .Calculation = xlManual
End With
'  READS DISTRIBUTION INFORMATION FROM ' TABELLE1 ' RANGE (B4:D4): KL = LOWEST, KM =
'  MOST LIKELY, KH = HIGHEST % YIELD INCREASE, AND KT = DISSEMINATION THRESHOLD)
kl = user_table.Range("B4"): km = user_table.Range("C4")
kh = user_table.Range("D4"): kt = user_table.Range("E4"): n = 100
ReDim check_matrix(1 To n), end_matrix(1 To n)
'  GENERATES INTEGER RANDOM NUMBERS Z BETWEEN 1 AND N SERVING AS NUMBERS FOR THE N
'  STRATA; RANDOM NUMBERS Z ARE THEN STORED IN DATA ARRAY CHECK_MATRIX (Z)
Do While strata < n
Randomize: z = Int((Rnd * n) + 1)
If check_matrix(z) = 0 Then
check_matrix(z) = 1: strata = strata + 1
end_matrix(strata) = z
'  RECEIVE A LIST OF RANDOMLY ORDERED INTEGER NUMBERS BETWEEN 1 AND N COLLECTED IN '
   END_MATRIX(Z)
End If
Loop
'  DETERMINES THE LOWER VALUE UT OF THE ADMISSIBLE RANDOM SAMPLING RANGE BETWEEN UT AND 1
ut = ((kt - kl)^2) / (kh - kl)* (km - kl)
' Determines strata size
strata_size = (1 - ut) / n
'  GENERATES ONE RANDOM NUMBER U FROM EACH STRATA AND CALCULATES RANDOM VARIATES K
'  DETERMINES THE CONDITIONAL RANDOM SAMPLING RANGE BETWEEN UT AND 1 ( UNIFORMLY
'  DISTRIBUTED) WHICH MUST LIE ABOVE THE DISSEMINATION THRESHOLD KT. FURTHER, IT
'  GENERATES ONE RANDOM NUMBER U AND ONE RANDOM VARIATE K FROM EACH STRATUM WITHIN UT AND
1.
'  THE PROBLEM IS TO DEFINE LOWER AND UPPER LIMITS OF U FOR THE 100 STRATA WHILE U IS
'  RESTRICTED TO UT AND 1.  THE FORMULA TO RESTRICT U TO AN UPPER AND LOWER LIMIT IS:
'  RND ( UPPER - LOWER) + LOWER. THEN, FOR EACH STRATUM, THESE UPPER AND LOWER LIMITS
'  MUST BE REPLACED BY UPPER LIMIT = UT+(STRATA_SIZE*END_MATRIX(I))AND
'  LOWER LIMIT = UT+(STRATA_SIZE*(END_MATRIX(I)-1)).
For i = 1 To n
Randomize:
u = Rnd * ((ut + (strata_size * end_matrix(i))) - (ut + (strata_size * (end_matrix(i) -
1)))) + (ut + (strata_size * (end_matrix(i) - 1))))
'  GENERATES RANDOM VARIATES K THROUGH INVERSE TRANSFORMATION OF THE TRIANGULAR CDF
If u < (km - kl) / (kh - kl) Then
k = kl + ((u * (kh - kl) * (km - kl)) ^ 0.5)
Else u = kh - (((1 - u) * (kh - kl) * (kh - km)) ^ 0.5)
End If
'  END SAMPLING
Next i
Calculate
End Sub
```

Appendix D-4: Routine for a Generalised Stochastic Dominance Program

This module documents the VBA source code for a stochastic dominance program that can discriminate distributions by FSD and SSD criteria; additionally, it can find the break-even risk aversion coefficient (B-RAC) for risk aversion and risk proneness, such that on each side of them a given distribution dominates. B-RACs are examined within the lower and upper bounds of $r_a(x)$ = 0 to 2 for risk aversion, and within $r_a(x)$ = 0 to -0.03 for risk proneness. The program draws heavily on the "riskroot" program developed by MCCARL (1988). The program can be directly applied when the VBA code is transferred to an EXCEL dialogue sheet. However, the user needs to develop own dialogue elements (boxes) for the display of the stochastic dominance results. He can freely choose the design of his dialogue boxes, but he requires four "list boxes" that must be named from "L1" to "L4".

```
Option Explicit
Sub STOCHASTIC_DOMINANCE()
Dim i, h, j, n, z, uu, k, NO_PAIRS, PAIR(), PAIR_P1(), PAIR_P2() As Integer
Dim d, a, NUMBER_TRIAL, NUMBER_SEARCH, BRAC_FOUND, NR_CROSS(), ADD_CROSS() As Integer
Dim DATA(), NUMBER, r, STEP_RAC, UD_SINGLE() As Double
Dim RACMAX, RACMIN, r1, r2, r3 As Double
Dim BRAC(), UD1(), UD2(), UD1_R(), UD2_R(), UD_SUM1(), UD_SUM2(), UD_DIFF() As Double
Dim c1, c2, c3, com_10, com_10a, com_11, com_12, com_13, com_14 As String
Dim SUM_X(), MEAN_X(), SD_X(), VAR_X(), SUM_X2() As Single
Dim PAIR_DESCPT(), MMM As Variant
Dim TAIL_CUT_%, TAIL_CUT As Integer
n = 100: k = 6
NUMBER_SEARCH = 100
For i = 1 To k - 1: NO_PAIRS = NO_PAIRS + (k - i): Next i
'EMPTY RESULT BOXES
For i = 1 To 4: DialogSheets("Dialog1").ListBoxes("L" & i).RemoveAllItems: Next i
'RE-DIMENSION of DATA AND VARIABLE ARRAYS
ReDim DATA(0 To n, k): ReDim ADD_CROSS(NO_PAIRS), NR_CROSS(NO_PAIRS)
ReDim PAIR_DESCPT(NO_PAIRS): ReDim PAIR(0 To n, NO_PAIRS): ReDim PAIR_P1(NO_PAIRS)
ReDim PAIR_P2(NO_PAIRS): ReDim UD1(0 To n, NO_PAIRS): ReDim UD2(0 To n, NO_PAIRS)
ReDim UD_SUM1(NO_PAIRS): ReDim UD_SUM2(NO_PAIRS): ReDim UD_SINGLE(NO_PAIRS)
ReDim UD_DIFF(NUMBER_SEARCH + 2, NO_PAIRS): ReDim BRAC(NUMBER_SEARCH + 2, NO_PAIRS)
ReDim SUM_X(k), MEAN_X(k), SD_X(k), VAR_X(k), SUM_X2(k)
ReDim UD1_R(0 To n, NO_PAIRS): ReDim UD2_R(0 To n, NO_PAIRS)
'SORT DATA
For j = 1 To k: For i = 1 To n
DATA(i, j) = Sheets("Tabelle2").Cells(3 + i, j + 1)
Next i: Next j
For j = 1 To k: For i = 2 To n
NUMBER = DATA(i, j)
For h = i - 1 To 1 Step -1
    If DATA(h, j) < DATA(h + 1, j) Then
    DATA(h + 1, j) = NUMBER
    Exit For
    Else DATA(h + 1, j) = DATA(h, j): DATA(h, j) = NUMBER
    End If
Next h: Next i: Next j
For j = 1 To k: For i = 1 To n
Next i: Next j
'END SORT

'STATISTICAL DESCRIPTION OF DISTRIBTUIONS
For j = 1 To k
For i = 1 To n
SUM_X(j) = SUM_X(j) + DATA(i, j)
SUM_X2(j) = SUM_X2(j) + (DATA(i, j) ^ 2)
Next i
MEAN_X(j) = SUM_X(j) / n: VAR_X(j) = (SUM_X2(j) / n) -(MEAN_X(j)) ^ 2: SD_X(j) =
VAR_X(j)^0.5
Next j
Call RESULTS_DES(n, j, k, MEAN_X, SD_X, DATA)
'END STATISTICS

'GENERATE SD-PAIRS AND CALCULATE NPV DIFFERENCES
```

```
h = 1
For d = 1 To k - 1
a = d + 1
Do Until a > k
For i = 1 To n
PAIR(i, h) = DATA(i, d) - DATA(i, a)
Next i
PAIR_DESCPT(h) = "DISTR:" & d & "-" & "DISTR:" & a
PAIR_P1(h) = d: PAIR_P2(h) = a
h = h + 1
a = a + 1
Loop
Next d
'END
'LEFT_TAIL CUT BY 2%
TAIL_CUT_% = 2: TAIL_CUT = Int(n * 5 / 100)

'IDENTIFY CDF CROSSING POINTS
For h = 1 To NO_PAIRS: For i = TAIL_CUT To n
If PAIR(i - 1, h) < 0 And PAIR(i, h) > 0 Or PAIR(i - 1, h) > 0 And PAIR(i, h) < 0 Then
ADD_CROSS(h) = 1: NR_CROSS(h) = NR_CROSS(h) + ADD_CROSS(h)
End If
Next i
'TEST DISTRIBUTIONS FOR FIRST-ORDER (FSD) AND SECOND-ORDER (SSD)STOCHASTIC DOMINANCE
If NR_CROSS(h) = 0 Then
c1 = "Comparing distribution " & PAIR_P1(h) & "  and " & PAIR_P2(h)
If PAIR(n / 2, h) > 0 Then
c2 = "The dominant distribution is " & PAIR_P1(h)
Else c2 = "The dominant distribution is " & PAIR_P2(h)
End If
c3 = "++++++++++++++++++++++++++++"
Call RESULTS_FSD(c1, c2, c3)
End If
Next h
'GENERALIZED STOCHASTIC DOMINANCE
'BRAC CALCULATION PROCEDURES FOR RISK AVERSION ( 0 < BRAC < 2)
For h = 1 To NO_PAIRS
If NR_CROSS(h) = 0 Then
GoTo JUMP_BACK
End If
uu = 1: BRAC_FOUND = 0
RACMIN = 0.000000001: RACMAX = 2: NUMBER_TRIAL = 0
STEP_RAC = (RACMAX - RACMIN) / NUMBER_SEARCH
PROC_BRAC:
NUMBER_TRIAL = NUMBER_TRIAL + 1
For r = RACMIN To RACMAX Step STEP_RAC
'LIMITS THE NUMBER OF BRAC ITERATIONS TO 10 RUNS
If NUMBER_TRIAL > 10 Then
MMM = MsgBox("No BRAC found between distribution " & PAIR_P1(h) & "and " & PAIR_P2(h),
vbOKOnly + vbExclamation)
Exit For: End If
'END LIMIT
UD_SUM1(h) = 0: UD_SUM2(h) = 0
Call UDCALC_AVERSE(NO_PAIRS, PAIR_P1, PAIR_P2, h, TAIL_CUT, i, n, r, UD1, UD2, UD_SUM1,
UD_SUM2, DATA, UD_SINGLE)
UD_DIFF(uu + 1, h) = UD_SINGLE(h)
BRAC(uu + 1, h) = r
If UD_DIFF(uu + 1, h) < 0 And UD_DIFF(uu, h) > 0 Or UD_DIFF(uu + 1, h) > 0 And UD_DIFF(uu,
h) < 0 Then
r1 = BRAC(uu, h): r2 = BRAC(uu + 1, h): r3 = (r1 + r2) / 2: r = r3
Call UDCALC_AVERSE(NO_PAIRS, PAIR_P1, PAIR_P2, h, TAIL_CUT, i, n, r, UD1, UD2, UD_SUM1,
UD_SUM2, DATA, UD_SINGLE)
'TEST UTILITY DIFFERENCE UD FOR BRAC R TO BE AROUND ZERO GIVEN ROOT TOLERANCE.
'IF TEST SUCCESS THE BRAC IS FOUND
If UD_SINGLE(h) < 0.0000001 And UD_SINGLE(h) > -0.0000001 Then
com_10 = "Comparing distribution " & PAIR_P1(h) & "  and " & PAIR_P2(h)
com_10a = "The distribution CDFs cross " & NR_CROSS(h) & "  times"
com_11 = "A BRAC has been found at r= " & Format(r, "0.0000000000") & " "
If UD_DIFF(uu + 1, h) < 0 And UD_DIFF(uu, h) > 0 Then
BRAC_FOUND = BRAC_FOUND + 1
com_12 = " below BRAC the dominant distribution is " & PAIR_P1(h)
com_13 = "above BRAC the dominant distribution is " & PAIR_P2(h)
Else com_12 = "below BRAC the dominant distribution is " & PAIR_P2(h)
com_13 = "above BRAC the dominant distribution is " & PAIR_P1(h)
End If
com_14 = "++++++++++++++++++++++++++++++++++++"
Call RESULTS_GSD(com_10, com_10a, com_11, com_12, com_13, com_14)
'SEARCH FOR A SECOND BRAC WHEN SEVERAL CDF CROSSING POINTS EXIST
If NR_CROSS(h) < 1 Or BRAC_FOUND = 2 Then
Exit For
Else RACMIN = r2: RACMAX = 2: STEP_RAC = (RACMAX - RACMIN) / NUMBER_SEARCH
uu = 1
```

```
GoTo PROC_BRAC
End If
'CONTINUE RAC ITERATION
Else RACMIN = r1: RACMAX = r2: STEP_RAC = (RACMAX - RACMIN) / NUMBER_SEARCH
uu = 1
GoTo PROC_BRAC
End If: End If
uu = uu + 1
Next r
JUMP_BACK:
Next h

'BRAC CALCULATION PROCEDURES FOR RISK PRONE ( -0.03 < BRAC < 0)
For h = 1 To NO_PAIRS
If NR_CROSS(h) = 0 Then
GoTo JUMP_BACK_R
End If
uu = 1: BRAC_FOUND = 0
RACMIN = -0.000000001: RACMAX = -0.03: NUMBER_TRIAL = 0
STEP_RAC = (RACMAX - RACMIN) / NUMBER_SEARCH
PROC_BRAC_R:
NUMBER_TRIAL = NUMBER_TRIAL + 1
For r = RACMIN To RACMAX Step STEP_RAC
'LIMITS THE NUMBER OF BRAC ITERATIONS TO 10 RUNS
If NUMBER_TRIAL > 10 Then
MMM = MsgBox("No BRAC found between distribution " & PAIR_P1(h) & "and " & PAIR_P2(h),
vbOKOnly + vbExclamation)
Exit For
End If
'END LIMIT
UD_SUM1(h) = 0: UD_SUM2(h) = 0
Call UDCALC_RISK(NO_PAIRS, PAIR_P1, PAIR_P2, h, TAIL_CUT, i, n, r, UD1_R, UD2_R, UD_SUM1,
UD_SUM2, DATA, UD_SINGLE)
UD_DIFF(uu + 1, h) = UD_SINGLE(h)
BRAC(uu + 1, h) = r
If UD_DIFF(uu + 1, h) < 0 And UD_DIFF(uu, h) > 0 Or UD_DIFF(uu + 1, h) > 0 And UD_DIFF(uu,
h) < 0 Then
r1 = BRAC(uu, h): r2 = BRAC(uu + 1, h): r3 = (r1 + r2) / 2: r = r3
Call UDCALC_RISK(NO_PAIRS, PAIR_P1, PAIR_P2, h, TAIL_CUT, i, n, r, UD1_R, UD2_R, UD_SUM1,
UD_SUM2, DATA, UD_SINGLE)
'TEST UTILITY DIFFERENCE UD FOR BRAC R TO BE AROUND ZERO GIVEN ROOT TOLERANCE.
'IF TEST SUCCESS THE BRAC IS FOUND
If UD_SINGLE(h) < 0.0000001 And UD_SINGLE(h) > -0.0000001 Then
com_10 = "Comparing distribution " & PAIR_P1(h) & "  and " & PAIR_P2(h)
com_10a = "The distribution CDFs cross " & NR_CROSS(h) & "  times"
com_11 = "A BRAC has been found at r= " & Format(r, "0.0000000000") & " "
If UD_DIFF(uu + 1, h) < 0 And UD_DIFF(uu, h) > 0 Then
BRAC_FOUND = BRAC_FOUND + 1
com_12 = " From -2 to BRAC the dominant distribution is " & PAIR_P2(h)
com_13 = "From BRAC to 0 the dominant distribution is " & PAIR_P1(h)
Else com_12 = "FROM -2 to BRAC the dominant distribution is " & PAIR_P1(h)
com_13 = "From BRAC to 0 the dominant distribution is " & PAIR_P2(h)
End If
com_14 = "++++++++++++++++++++++++++++++++++++"
Call RESULTS_RSD(com_10, com_10a, com_11, com_12, com_13, com_14)
'Search for a second BRAC when several CDF crossing points exist
If NR_CROSS(h) < 1 Or BRAC_FOUND = 2 Then
Exit For
Else RACMIN = r2: RACMAX = -0.03: STEP_RAC = (RACMAX - RACMIN) / NUMBER_SEARCH
uu = 1
GoTo PROC_BRAC_R
End If
'CONTINUE RAC ITERATION
Else RACMIN = r1: RACMAX = r2: STEP_RAC = (RACMAX - RACMIN) / NUMBER_SEARCH
uu = 1
GoTo PROC_BRAC_R
End If
End If
uu = uu + 1
Next r
JUMP_BACK_R:
Next h

'SHOW RESULT TABLE
DialogSheets("Dialog1").Show
End Sub

'CALCULATE UTILITY DIFFERENCES FOR RISK AVERSION
Function UDCALC_AVERSE(NO_PAIRS, PAIR_P1, PAIR_P2, h, TAIL_CUT, i, n, r, UD1, UD2, UD_SUM1,
UD_SUM2, DATA, Optional UD_SINGLE)
For i = 1 To n
UD1(i, h) = -(Exp(-r * DATA(i, PAIR_P1(h))))
```

```
UD2(i, h) = -(Exp(-r * DATA(i, PAIR_P2(h))))
UD_SUM1(h) = UD_SUM1(h) + UD1(i, h)
UD_SUM2(h) = UD_SUM2(h) + UD2(i, h)
Next i
UD_SINGLE(h) = UD_SUM1(h) - UD_SUM2(h)
End Function

'CALCULATE UTILITY DIFFERENCES FOR RISK PRONENESS
Function UDCALC_RISK(NO_PAIRS, PAIR_P1, PAIR_P2, h, TAIL_CUT, i, n, r, UD1_R, UD2_R,
UD_SUM1, UD_SUM2, DATA, Optional UD_SINGLE)
For i = 1 To n
UD1_R(i, h) = ((Exp(-r * DATA(i, PAIR_P1(h))))) / 1E+50
UD2_R(i, h) = ((Exp(-r * DATA(i, PAIR_P2(h))))) / 1E+50
UD_SUM1(h) = UD_SUM1(h) + UD1_R(i, h)
UD_SUM2(h) = UD_SUM2(h) + UD2_R(i, h)
Next i
UD_SINGLE(h) = UD_SUM1(h) - UD_SUM2(h)
End Function

'SD-RESULTS
Sub RESULTS_FSD(c1, c2, c3)
Dim dia As Object
Set dia = DialogSheets("Dialog1").ListBoxes("L1")
dia.AddItem Text:=c1: dia.AddItem Text:=c2: dia.AddItem Text:=c3
End Sub

Sub RESULTS_GSD(com_10, com_10a, com_11, com_12, com_13, com_14)
Dim dia As Object
Set dia = DialogSheets("Dialog1").ListBoxes("L2")
dia.AddItem Text:=com_10: dia.AddItem Text:=com_10a: dia.AddItem Text:=com_11
dia.AddItem Text:=com_12: dia.AddItem Text:=com_13: dia.AddItem Text:=com_14
End Sub

Sub RESULTS_RSD(com_10, com_10a, com_11, com_12, com_13, com_14)
Dim dia As Object
Set dia = DialogSheets("Dialog1").ListBoxes("L4")
dia.AddItem Text:=com_10: dia.AddItem Text:=com_10a: dia.AddItem Text:=com_11
dia.AddItem Text:=com_12: dia.AddItem Text:=com_13: dia.AddItem Text:=com_14
End Sub

Sub RESULTS_DES(n, j, k, MEAN_X, SD_X, DATA)
Dim dia As Object
Dim a, b, c, d  As Single
Dim na, nb, nc, nd As Integer
Set dia = DialogSheets("Dialog1").ListBoxes("L3")
For j = 1 To k
a = Format(MEAN_X(j), "0.00"): b = Format(SD_X(j), "0.00"): c = Format(DATA(1, j), "0.00")
d = Format(DATA(n, j), "0.00")
na = 2 * Len(a): nb = 2 * Len(b): nc = 2 * Len(c): nd = 2 * Len(d)
dia.AddItem Text:="DSTRB:  " & j & "     " & a & Space(19 - na) & b & Space(19 - nb) & c &
Space(19 - nc) & d & Space(19 - nd)
Next j
End Sub
```

Appendix D-5: Routine for Induced Rank Correlation Among Multiple Variables

This module documents the VBA source code for the multivariate induced correlation method described in IMAN and CONOVER (1981). The major variables in this procedure are : IN_PUT() = initial input data; INPUT_RANK() = ranking scores; C_MTX() = C; P_MTX() = P; M_MTX() = M; O_MTX() = M_B^*, S_MTX() = S; S_MTX_TRANS() = S^T; Q_MTX() = Q; T_MTX() = T; INPUT_SORT() = ordered input values; INPUT_B() = R_B*; QUTPUT() = X_B^* ; n = sample size; k = number of variables.

```
Option Explicit
Sub INDUCED_RANK_CORRELATION()
Dim i, j, s, n, k, p, z, zz, l, ll, u, icol, IROW As Integer
Dim RANK(), INPUT_RANK(), INPUT_B(), M_MTX(), S_MTX(), S_MTX_TRANS(), I_PIV() As Single
Dim RANK_DIFF, SPEARMAN, INDXR(), INDXC(), big, DUMMY, PIV_INV, OUTPUT() As Single
Dim C_MTX(), P_MTX(), Q_MTX(), Q_INV_MTX(), COV_MTX(), SUM_C, SUM_T As Single
Dim P_MTX_TRANS(), E_INPUT(), E_PROD(), F_INPUT(), VAR_INPUT(), T_MTX() As Single
Dim INPUT_SORT(), NUMBER, IN_PUT() As Single
n = 15: k = 6
ReDim RANK(n, k), INPUT_RANK(n, k), INPUT_B(n, k), M_MTX(k, k), Q_INV_MTX(k, k)
ReDim S_MTX(k, k), C_MTX(k, k), P_MTX(k, k), Q_MTX(k, k), OUTPUT(n, k)
ReDim I_PIV(k), INDXR(k), INDXC(k), S_MTX_TRANS(k, k), IN_PUT(n, k)
ReDim P_MTX_TRANS(k, k), E_INPUT(k), VAR_INPUT(k), T_MTX(k, k)
ReDim E_PROD(k, k), F_INPUT(k), COV_MTX(k, k), INPUT_SORT(n, k)

'READ RAW INPUT DATA
For j = 1 To k: For i = 1 To n
IN_PUT(i, j) = Sheets("Tabelle3").Cells(2 + i, j + 1)
Next i: Next j
'CALCULATE RANKS FROM INPUT DATA REPLACING RAW INPUT DATA
For j = 1 To k: For i = 1 To n: For s = 1 To n
If IN_PUT(s, j) <= IN_PUT(i, j) Then
INPUT_RANK(i, j) = INPUT_RANK(i, j) + 1
End If
Next s: Next i: Next j
'END

'EXPECTED VALUE, VARIANCE-COVARIANCE MATRIX (COV_MTX) AND 'CORRELATION MATRIX 'T'(T_MTX)
FROM INPUT RANKS
For j = 1 To k: For i = 1 To n
E_INPUT(j) = E_INPUT(j) + (INPUT_RANK(i, j) / n)
F_INPUT(j) = F_INPUT(j) + (INPUT_RANK(i, j) ^ 2 / n)
Next i
VAR_INPUT(j) = F_INPUT(j) - (E_INPUT(j) ^ 2)
Next j
For z = 1 To k: For j = z + 1 To k: For i = 1 To n
E_PROD(z, j) = E_PROD(z, j) + (INPUT_RANK(i, z) * INPUT_RANK(i, j) / n)
Next i: Next j: Next z
For z = 1 To k: For j = z + 1 To k
COV_MTX(z, j) = E_PROD(z, j) - (E_INPUT(z) * E_INPUT(j))
T_MTX(z, j) = COV_MTX(z, j) / (Sqr(VAR_INPUT(z)) * Sqr(VAR_INPUT(j)))
T_MTX(j, z) = T_MTX(z, j): COV_MTX(j, z) = COV_MTX(z, j)
Next j
T_MTX(z, z) = 1: COV_MTX(z, z) = VAR_INPUT(z)
Next z
'END PROCEDURE

'SORT INPUT DATA
For j = 1 To k: For i = 1 To n
INPUT_SORT(i, j) = IN_PUT(i, j)
Next i: Next j
For j = 1 To k: For i = 2 To n
NUMBER = INPUT_SORT(i, j)
For z = i - 1 To 1 Step -1
    If INPUT_SORT(z, j) < INPUT_SORT(z + 1, j) Then
    INPUT_SORT(z + 1, j) = NUMBER
    Exit For
    Else INPUT_SORT(z + 1, j) = INPUT_SORT(z, j): INPUT_SORT(z, j) = NUMBER
    End If
Next z: Next i: Next j
'END SORT
'CHOLESKY DECOMPOSIOTION OF 'C' AND 'T' INTO TRIANGULAR MATRIXES 'P' AND 'Q'
For i = 1 To k: For j = 1 To k
```

```
C_MTX(i, j) = Worksheets("Tabelle2").Cells(2 + i, 1 + j)
P_MTX(i, j) = 0: Q_MTX(i, j) = 0
Next j: Next i
For i = 1 To k: For j = i To k
SUM_C = C_MTX(i, j): SUM_T = T_MTX(i, j)
For z = i - 1 To 1 Step -1
SUM_C = SUM_C - (P_MTX(i, z) * P_MTX(j, z))
SUM_T = SUM_T - (Q_MTX(i, z) * Q_MTX(j, z))
Next z
If i = j Then
If SUM_C < 0 Then
SUM_C = -SUM_C
End If
P_MTX(i, i) = Sqr(SUM_C)
Else
P_MTX(j, i) = SUM_C / P_MTX(i, i)
End If
If i = j Then
If SUM_T < 0 Then
SUM_T = -SUM_T
End If
Q_MTX(i, i) = Sqr(SUM_T)
Else
Q_MTX(j, i) = SUM_T / Q_MTX(i, i)
End If
Next j: Next i
For i = 1 To k: For j = 1 To k
P_MTX_TRANS(j, i) = P_MTX(i, j)
Next j: Next i
'END DECOMPOSITION

'MATRIX INVERSION OF Q INTO Q(-1)
For j = 1 To k
I_PIV(j) = 0
Next j
For j = 1 To k: For i = 1 To k
Q_INV_MTX(i, j) = Q_MTX(i, j)
Next i: Next j
For i = 1 To k
big = 0
For j = 1 To k
If Not I_PIV(j) = 1 Then
For zz = 1 To k
If I_PIV(zz) = 0 Then
If Abs(Q_INV_MTX(j, zz)) >= big Then
big = Abs(Q_INV_MTX(j, zz)): IROW = j: icol = zz
End If
Else
If I_PIV(zz) > 1 Then
GoTo ende
End If
End If
Next zz
End If
Next j
I_PIV(icol) = I_PIV(icol) + 1
If Not IROW = icol Then
For l = 1 To k
DUMMY = Q_INV_MTX(IROW, l)
Q_INV_MTX(IROW, l) = Q_INV_MTX(icol, l)
Q_INV_MTX(icol, l) = DUMMY
Next l
End If
INDXR(i) = IROW: INDXC(i) = icol
PIV_INV = 1 / Q_INV_MTX(icol, icol)
Q_INV_MTX(icol, icol) = 1
For l = 1 To k
Q_INV_MTX(icol, l) = Q_INV_MTX(icol, l) * PIV_INV
Next l
For ll = 1 To k
If Not ll = icol Then
DUMMY = Q_INV_MTX(ll, icol): Q_INV_MTX(ll, icol) = 0
For l = 1 To k
Q_INV_MTX(ll, l) = Q_INV_MTX(ll, l) - Q_INV_MTX(icol, l) * DUMMY
Next l
End If
Next ll
Next i
'END MATRIX INVERSION

'CALCULATE S = P*Q^-1
For i = 1 To k: For u = 1 To k: For j = 1 To k
```

```
S_MTX(i, u) = S_MTX(i, u) + (P_MTX(i, j) * Q_INV_MTX(j, u))
S_MTX_TRANS(u, i) = S_MTX(i, u)
Next j: Next u: Next i
'CALCULATE RB = RS'
For i = 1 To n: For u = 1 To k: For j = 1 To k
INPUT_B(i, u) = INPUT_B(i, u) + (INPUT_RANK(i, j) * S_MTX_TRANS(j, u))
Next j: Next u: Next i
'END PROCEDURE

'CALCULATE RANK CORRELATION MATRIX 'M' OF RB (INPUT_B) AND COMPARE 'M' WITH 'C'
For j = 1 To k: For i = 1 To n: For s = 1 To n
If INPUT_B(s, j) <= INPUT_B(i, j) Then
RANK(i, j) = RANK(i, j) + 1
End If
Next s: Next i: Next j
For j = 1 To k: For p = j + 1 To k
RANK_DIFF = 0
For i = 1 To n
RANK_DIFF = RANK_DIFF + (RANK(i, j) - RANK(i, p)) ^ 2
Next i
SPEARMAN = 1 - ((6 * RANK_DIFF) / (n * (n ^ 2 - 1)))
M_MTX(j, p) = SPEARMAN: M_MTX(p, j) = SPEARMAN
Next p:
M_MTX(j, j) = 1
Next j
'RE-ARRANGE INPUT DATA AS 'OUTPUT' WITH THE DESIRED RANK CORRELATION
For j = 1 To k
For i = 1 To n
OUTPUT(i, j) = INPUT_SORT(RANK(i, j), j)
Next i: Next j
'END PROCEDURE
ende:
End Sub
```